Series II, Volume 5 March 21, 1960 Number 3

BULLETIN

OF THE

AMERICAN PHYSICAL SOCIETY

INCLUDING THE

PROGRAMME OF THE

1960 DETROIT MEETING

March 21–24

PUBLISHED BY THE AMERICAN PHYSICAL SOCIETY, COLUMBIA UNIVERSITY, NEW YORK 27, NEW YORK
SEVEN ISSUES EACH YEAR

BULLETIN

of the

AMERICAN PHYSICAL SOCIETY

Published seven times per year

Subscription price: $5.00 per year

Back number prices: $4.00 for the triennial Membership list; $1.00 for other issues

The Bulletin of the American Physical Society is published seven times a year, once in January, twice in March, once in April, once in June, once in November, and once in December, at Prince and Lemon Streets, Lancaster, Pennsylvania. Correspondence should be addressed to American Physical Society, Columbia University, New York 27, New York.

Entered as second class matter, December 27, 1949, at the post office at Lancaster, Pa., under the Act of August 24, 1912.

Acceptance for mailing at a special rate of postage provided for in paragraph (d-2), Section 34.40, P. L. & R. of 1948, authorized Nov. 30, 1948.

Table of Contents

Page

Programme of the 1960 March meeting at Detroit:

- Preamble 142
- Epitome 144
- Main Text 146
- Index 205
- Hotel reservation form 209

Minutes of the 1959 August Meeting at Honolulu 211

Minutes of the 1959 Thanksgiving Meeting at Cleveland 211

Minutes of the 1959 Winter Meeting at Pasadena 213

Preliminary announcement of the 1960 June meeting at Montreal 214

Announcements of topical conferences 215

Calendar of meetings and deadlines 216

Rules and instructions for the preparation of abstracts 217

Officers of the Society for 1960 218

March 21, 1960 Series II, Vol. 5, No. 3

BULLETIN

OF THE

AMERICAN PHYSICAL SOCIETY

1960 "March" Meeting in Detroit, March 21–24, 1960

THE **1960 "March" meeting** of The American Physical Society will be held in Detroit from **Monday, March 21, through Thursday, March 24,** the last of these four days being confined, however, to our Division of High-Polymer Physics. This and our Divisions of Solid State Physics and Chemical Physics come very close indeed to monopolizing the convention. Perhaps we should not be disappointed at this, the Council having established the sequence of "March meetings" for precisely the purpose that they are now serving; but there was also hope that these would serve as general meetings for the physicists of the region, a hope that is fading. The role of the Secretary in preparing and organizing this meeting has been minimal, the three Divisions having built up their own programmes. Particular note should be made of the labors of E. Burstein and F. Herman who spent a long and heavy day at the office of the Society, distributed all of the abstracts (267 of them) in solid-state physics into 26 sessions, and found names for the sessions and sprinkled the invited papers among them; and of H. Leaderman who rendered the same service to high-polymer physics. No speakers were invited to speak on subjects outside of the fields of the Divisions, for the Secretary assumed that nobody would come to hear about such subjects. It is conceivable that the assumption was wrong and that Detroit will be full of Divisional physicists who would have liked to broaden their knowledge.

This will be our third meeting in Detroit. The first was imagined and realized, and both the first and second were managed, by the late G. P. Brewington whom we thankfully remember. In 1942 there were 28 contributed papers and 95 registrants (this was when wartime conditions made travel difficult) and in 1954 there were 197 of the one and 741 of the other. Notably more difficult will be the situation faced by Professor Brewington's successor, Professor R. V. Adams of Wayne State University. This meeting counts 318 contributed papers, short by only five of the number (a record for a March meeting) attained last year at Cambridge! If the attendance reaches last year's dimension, it will pass 1400. In the previous Detroit meetings the sessions were scattered over the town and over Ann Arbor; but the dispersal had disadvantages, and Professor Adams has succeeded in condensing our whole great convention into an area of a two-block radius, a feat which speaks well for him and for the builders of Detroit. Some of these auditoria cost money, and this fact is reflected in the registration fee. Incidentally two of them are in the magnificent art gallery of Detroit, the collections of which will set up the severest competition that the speakers have ever had.

Hotels. A form is printed on page 209 of this Bulletin, which our members are asked to use. The Park Shelton hotel is situated in the middle of the meeting area, the Sheraton-Cadillac and the Statler-Hilton about two miles from it in the heart of downtown Detroit (but taxis cost only about $1.25 and may be shared by four people).

The **registration desk** will be in the Community Arts Auditorium of Wayne State University, which is located on Kirby Street near Cass Avenue. Blackboards will be set up there for notice of messages, notice of changes in the placing of sessions if any are necessitated, and notices of post-deadline papers if any. Tickets for the banquet will be sold at the desk so long as they last and so will tickets for the cocktail party, if required. Guidance to the meeting halls away from the Center will be provided at the desk if it is needed.

The **registration fee** will be two dollars. The amount by which this exceeds our heretofore habitual fee will be compensated amply by the fact that it will not be necessary to take public or private transportation to get from any session to any other.

For the **invited papers of the three Divisions** the reader is referred to the Main Text and the Epitome. Special mention however, is, accorded to the **Oliver E. Buckley Lecture** to be delivered on

Tuesday morning at 11:15 in our largest hall by Benjamin Lax, the latest to receive the Oliver E. Buckley Solid-State Physics Prize and the first to receive it since the lamented death of Dr. Buckley (on December 14, 1959). The Division of Solid-State Physics has succeeded in copying the precedent of past years by so disposing its sessions that none of them coincides in time with this event.

The **banquet of the Society will be held on Tuesday evening** in the Banquet Hall of the Engineering Society of Detroit, which is in the "meeting area." The price will be four dollars. The deadline hour, after which only a very limited number of tickets may be sold, is to be three o'clock on Monday afternoon. If you expect to arrive later, send a check (made out to American Physical Society) to Professor R. V. Adams, Wayne State University, Detroit 2, Michigan. You may prefer to do this anyhow so as to save your time on Monday. The after-dinner speakers will be announced on the blackboard near the registration desk if not in this place.

(Speaking of meals, a cafeteria will be set up in the hall just mentioned to serve luncheons to our members and guests, the restaurants of the neighborhood not being large enough to take the whole of so great a crowd as we expect. The Society may have to make a guarantee to maintain this special service.)

A **cocktail party** will be held at the Park Shelton Hotel on the Monday beginning at six. We shall try to find an angel to pick up the check, but our members will be well advised to set aside $1.50 per person in case the angel does not materialize. There might also be a gratuitous beer party: look at the blackboard.

The **Council** of the American Physical Society will meet at a time and place of which its members will be notified, and there will be **Business Meetings of our three Divisions** at the times and places indicated in Epitome and Main Text.

Post-deadline ten-minute papers pertaining to very recent achievements of very special importance will be considered for admission to the "special supplementary programme" if the abstracts are received not later than Wednesday, March 16, at the office of Professor R. V. Adams, Wayne State University, Detroit 2, Michigan. Type at the top of each such abstract the words "POST DEADLINE ABSTRACT FOR DETROIT MEETING." The titles of such as are accepted will be written on blackboards near the registration desk, and the papers may be given under the usual ten-minute rule in Session XA, or possibly at the ends of relevant sessions if the relevant sessions are short enough to permit of extension.

A **preliminary announcement of the 1960 June meeting in Montreal** appears on page 214 of this Bulletin, and on page 215 announcements of various topical conferences. **This announcement about Montreal is of unusual importance because of the necessity of making hotel reservations early.** See the previous (Houston) issue of this Bulletin for the announcement of the Washington meeting. On page 216 are published the calendar of meetings and deadlines up to the end of the summer (there will be no Summer Meeting on the West Coast this year) and below it the rules and instructions for the preparation of abstracts which we commend to the attention of every member, as also we commend the instructions as to mailing which follow upon the calendar.

Errata pertaining to the contents of this issue will be published in a later issue of this Bulletin if received not later than Monday, March 28, by Miss Ruth Bryans, 335 East 45 Street, New York 17, New York. Do not send in a copy of your abstract marked with corrections! Write out every correction in the form "instead of . . . read . . . ." Add nothing.

KARL K. DARROW, *Secretary*
American Physical Society
Columbia University
New York 27, New York

EPITOME OF THE 1960 DETROIT MEETING

(Personal names are those of invited speakers. DSSP stands for Division of Solid-State Physics, DHPP for Division of High-Polymer Physics. DCP for Division of Chemical Physics.)

Monday Morning

10:00 A. DSSP Symposium on noncrystalline solids: Turnbull, Keating, Bray, King. Auditorium, Institute of Arts.

10:00 B. Irradiation effects (metals): Lambe. Lecture Hall, Institute of Arts.

10:00 BA. Moriya, Suhl; magnetism (theory). Rackham.

10:00 C. Sladek; transport properties. Engineering.

10:00 CA. Williams; compound semiconductors I. Community Arts.

10:00 D. Internal friction and diffusion. McGregor Room L.

Monday Afternoon

2:00 DA. Chemical Physics. Lecture Room, Institute of Arts.

2:15 E. DSSP Symposium on dislocations: Gilman, Wilsdorf, Patel, Alers. Auditorium, Institute of Arts.

2:15 F. Electron-spin resonance. Engineering.

2:15 FA. Fritzsche; transport properties (silicon and germanium I). McGregor Room L.

2:15 G. Ham; energy-band theory, magnetic susceptibilities. Rackham.

2:15 GA. Superconductivity and thermal properties. Community Arts.

2:15 H. Crystal growth. McGregor Room B.

Tuesday Morning

9:30 I. Balluffi, Moore; Oliver E. Buckley Lecture by Benjamin Lax; Business Meeting of DSSP. Auditorium, Institute of Fine Arts.

9:30 IA. Irradiation effects (compounds). Lecture Hall, Institute of Arts.

9:30 J. X-ray and neutron scattering. McGregor Room B.

9:30 JA. Elastic properties. Rackham.

9:30 K. Mostly noncrystalline solids. Community Arts.

9:30 KA. General physics. McGregor, Room L.

9:30 L. DHPP: McIntyre, Wall, contributed papers. Engineering.

Tuesday Afternoon

2:00 M. DHPP: Boney, contributed papers; Business Meeting of DHPP. Engineering.

2:15 MA. DSSP Symposium on radiation effects in solids: Koehler, Nilan, Vineyard, Watkins. Auditorium, Institute of Arts.

2:15 N. Nuclear magnetic resonance. McGregor Room L.

2:15 NA. Magneto-optical properties and cyclotron resonance; Scott, McGregor Room B.

2:15 O. Theory. Rackham.

2:15 OA. Diffusion (mostly noble metals). Community Arts.

2:15 P. DCP Symposium: Eberhardt, Peters, Lassettre. Business Meeting of DCP. Lecture Hall, Institute of Arts.

Tuesday Evening

7:00 Banquet of The American Physical Society; speakers to be announced. Banquet Hall, Engineering Society of Detroit.

Wednesday Morning

9:30 Q. DSSP Symposium on electronic states of metals: Cohen, Galt, Luttinger, Portis. Auditorium, Institute of Arts.

9:30 QA. Irradiation effects (alkali halides). Lecture Hall, Institute of Arts.

9:30 R. Compound semiconductors II and others. McGregor Room L.

9:30 RA. Newman; magnetism (experimental). Rackham.

9:30 S. Mostly dislocations. Community Arts.

9:30 T. DHPP: Keith, Hoffman, Peterlin, contributed papers. Engineering.

Wednesday Afternoon

2:00 U. DHPP: contributed papers. Engineering.

2:00 V. Transport properties (silicon and germanium II). Lecture Hall, Institute of Arts.

2:00 VA. Irradiation effects (silicon and germanium). McGregor Room L.

2:00 W. Hass; lattice vibrations. Rackham.

2:00 X. Insulators. Community Arts.

2:15 XA. Post-deadline papers, if any. McGregor Room B.

Thursday Morning

9:30 Y. DHPP: McCormick, Smith; contributed papers. Community Arts.

Thursday Afternoon

2:00 Z. DHPP; Powell, McCrum, contributed papers. Community Arts.

PROGRAMME

MONDAY MORNING AT 10:00

Auditorium, Institute of Arts

(O. L. ANDERSON presiding)

DSSP Symposium on Noncrystalline Solids

A1. Crystallization Kinetics and Glass Formation. D. TURNBULL, General Electric Research Laboratory. (40 min.)

A2. Radiation-Induced Amorphism in Diamond. D. T. KEATING, *Brookhaven National Laboratory.* (30 min.)

A3. Nuclear Magnetic Resonance Studies of the Structure of Glass. P. J. BRAY, *Brown University.* (30 min.)

A4. Acoustic Absorption in Silica at Low Temperatures. J. C. KING, *Bell Telephone Laboratories.* (30 min.)

MONDAY MORNING AT 10:00

Lecture Hall, Institute of Arts

(R. SMOLUCHOWSKI presiding)

Irradiation Effects: Metals

B1. Effective Temperature of Radiation Annealing.* J. R. TOWNSEND, *University of Pittsburgh.*—Lattice excitation resulting from irradiation by high-energy particles may result in appreciable annealing of defects introduced by collisions producing atomic displacement. Considerations of this annealing by Seitz[1] and others have been in terms of the effect of thermal spikes on a specified type of annealing process. The present approach differs from this in that the average steady-state energy spectrum of the excited lattice atoms is compared with the spectrum produced by thermal means alone. This results in a calculated effective temperature at which purely thermal annealing becomes equivalent to that produced by the radiation. A conservative estimate is based on a model of isolated collisions and use of a hard-sphere interaction potential. For annealing processes having an activation energy of 1 ev, for example, it is found that 1 μa/cm^2 of 15-Mev deuterons is equivalent to an annealing temperature of about 200°K. The effective temperature is a very insensitive function of the flux density and the activation energy. The method predicts temperatures which can be compared directly with experimental annealing results to test this interpretation of radiation annealing.

* Work done at the Sarah Mellon Scaife Radiation Laboratory and supported by the U. S. Air Force Cambridge Research Center, Air Research and Development Command.

[1] F. Seitz and J. S. Koehler, Advances in Solid State Phys. 2, 356 (1956).

B2. Creation of Defects near "Hot Spots" in Metal Crystals. W. R. HELLER, *IBM Yorktown Research Center.*—There is continuing interest in a more complete and rigorous theory of the defect pattern produced by the sudden communication to a metal lattice atom of energies ranging from several up to several hundred electron volts. The following formulation of this familiar problem has been studied. A model crystalline material is characterized by its macroscopic thermal constants. One then considers the diffusion of heat and of a single type of defect away from a localized transient source of thermal energy and of the defects in question. This source is allowed to operate over distances and times of typical atomic magnitudes. Numerical solution of the coupled nonlinear equations, including recombination, shows that quenched-in disorder is indeed predicted, but is very small. It is known from experiments measuring radiation damage in metals under comparable circumstances that quite appreciable quantities of frozen-in defects are produced, especially at low ambient temperatures. Neither the present more detailed model of a "thermal spike" nor earlier versions predict effects as large as the observed defect density. One is apparently forced to the conclusion that a new mechanism of defect production is needed, leading to propagation of defects outside the locally heated zone surrounding a struck atom.

B3. Production and Recovery of Radiation Damage in Ag, Au, Fe, and Ni.* R. M. WALKER, J. W. CORBETT, AND E. L. FONTANELLA, *General Electric Research Laboratory.*—The resistivity changes produced by bombardment with ~1.4-Mev electrons have been measured in Ag, Au, Fe, and Ni. In Ag and Au (irradiation temperature $\lesssim$10°K) the resistivity changes in units of ohm-cm per (electron/cm^2) are Ag, 5.3×10^{-27} and Au, $0\pm2\times10^{-30}$. In Fe and Ni (irradiation temperature ~20°K) the values are: Fe, 6.7×10^{-26} and Ni, 2.1×10^{-26}. Annealing experiments up to room temperature also have been performed, and in each material (excluding gold which did not damage observably) there are several temperature ranges in which recovery is observed. The lowest temperature recovery stage, analogous to stage I recovery in irradiated Cu,[1] is found to dominate in every case. The temperature interval and total fractional recovery characteristic of this dominant recovery stage have the following values in the materials studied: Ag (10°K–30°K)—50%, Fe (50°K–120°K)—80%, and Ni (40°K–70°K)—70%. Each of these dominant recovery stages shows structure similar to that previously studied in Cu.[1] The implication of these results to the interpretation of radiation damage in these materials will be discussed.

[1] J. W. Corbett, R. B. Smith, and R. M. Walker, Phys. Rev. 114, 1452 (1959).

* Sponsored by Air Force Cambridge Research Center.

B4. Effect of Fast-Neutron-Induced Defects on the Internal Friction and Young's Modulus of Copper. V. K. PARÉ AND D. O. THOMPSON, *Oak Ridge National Laboratory.**—Studies on the pinning of dislocations in pure copper by radiation defects have been continued in the range immediately above room temperature. The technique is to measure changes in internal friction and Young's modulus during fast-neutron bombardment at constant temperature. The pinning rate appears to be the same at 320°K as at 308°K. At 334°K the initial pinning rate is still the same, but an additional contribution (presumably representing another pinning defect) begins to appear and develops according to an average delay time of several hours. This delay is interpreted as the average time required for the additional defects to reach the dislocations. The final pinning rate is roughly twice that at 308°K and 320°K. At 355°K the delay time is too small to measure, the pinning rate is not increased further, and the rate is actually reduced in the later stages of the run, presumably because of annealing of the pinning defects. In most cases the best representation of the data is by two components, as if two types of dislocations, with different defect capture probabilities, are being pinned.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

B5. Fission-Fragment Damage in Copper and Aluminum. C. E. KLABUNDE, T. H. BLEWITT, AND R. R. COLTMAN, *Oak Ridge National Laboratory.**—Copper and aluminum were doped with U^{235} (0.1%) and bombarded with thermal neutrons at 4°K in the ORNL Graphite Reactor to compare fission-fragment damage with fast-neutron damage. Samples doped with U^{238} as controls demonstrated that nonfissile uranium did not affect the characteristics of neutron damage. The dose (ϕ)-resistivity (ρ) curve of U^{235} doped copper demonstrated (a) that the measured damage rate near the origin was 100 times that of pure copper in agreement with theoretical estimates of Seitz, and (b) that a curve of the form $\Delta\rho = A(1-e^{-B\phi}) + C\phi$ was obeyed. The first term (radiation annealing) saturated at 3×10^{-7} ohm-cm, whereas the coefficient C had a value of 7×10^{-2} ohm-cm/neutrons/cm^2. Similar results were observed in the case of aluminum. The annealing kinetics of U^{235} doped aluminum and copper were similar to those of pure aluminum and copper, respectively, with the exception that the magnitude of the annealing peak at 30°K was not as great as for pure copper. It was found that the magnitude of the peak could be increased by decreasing the dose. In the case of aluminum, the U^{235} doped annealing curves fell on the pure aluminum curves when the radiation induced resistivity was the same.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

B6. Catalytic Activity of Irradiated Copper.* AIJA SPILNERS AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.*—It has been shown previously that preirradiation of metallic preactivated copper with 10^{15} protons of 350-Mev energy lowers the activation energy for decomposition of formic acid by a factor of about two and at the same time lowers the reaction rate. In order to distinguish between the various models of this unusual behavior, additional measurements of catalytic activity of electrolytically polished copper have been made. It appears that in this case too the reaction rate and the activation energy is low. It is suggested then that the influence of proton irradiation can be interpreted as a result of accelerated diffusion, in particular, surface diffusion. This increased surface mobility eliminates surface sites introduced by preactivation, which are presumably strain free, and leaves only those which are more stable, such as strained regions surrounding a dislocation emerging at the surface.

* Research supported by a U. S. Atomic Energy Commission contract.

B7. Resistivity Measurements on Cu-Al upon Electron and Gamma Irradiation. M. S. WECHSLER AND R. H. KERNOHAN, *Oak Ridge National Laboratory.**—Neutron irradiation of α-phase Cu-Al (15 at. % Al) has been shown[1] to produce a decrease in resistivity of about 0.18 μ ohm-cm. The measurements indicate that the alloy as normally prepared is in a metastable state below 200°C[2] and that the metastability is eliminated upon irradiation, with an attendant decrease in resistivity. Experiments are described in which it is seen that the decrease in resistivity may be produced by 1–2 Mev electron and by Co^{60} gamma irradiations as well as reactor neutron irradiation. The magnitude of the decrease in resistivity is the same for the three types of radiations. Also, the same kinetic law (roughly second-order kinetics) appears to be followed in each case. However, the rate of decrease in resistivity depends upon the type of radiation, the temperature of irradiation, and the flux. The relative effectiveness of the three types of irradiations will be discussed.

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

[1] M. S. Wechsler and R. H. Kernohan, J. Phys. Chem. Solids **7**, 307 (1958).

[2] M. S. Wechsler and R. H. Kernohan, Acta Met. **7**, 599 (1959).

B8. Radiation Inhibited Diffusion in Brass.* R. ARNDT AND R. L. HINES, *Northwestern University.*—It is well known that when brass is heated in a vacuum the zinc diffuses to the surface and evaporates. If the brass is bombarded by energetic particles one would expect that the diffusion would be enhanced. To test this, the reflection coefficient of bombarded brass was measured since it gives an indication of the zinc content in the surface layer. Preliminary results indicate that ion bombardment inhibits diffusion of zinc in the surface layer affected by the bombardment. The brass samples were heated for several minutes at 236°C and at the same time bombarded by 23-kev A^+ ions at a particle flux density of the order of 10^{14} ions/cm^2 sec. Prior to bombardment the samples were annealed, polished, and etched. Studies of the reflection coefficient as a function of particle flux density show that the effect is constant over the range of 10^{13} to 10^{14} ions/cm^2 sec. A comparison is made with copper under similar conditions to determine the effect of the beam when no diffusion is present. Possible mechanisms for the explanation of these results will be discussed.

* Supported by the U. S. Atomic Energy Commission.

B9. Search for Irradiation Induced Surface Damage.* R. M. WORTMAN AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.*—The field emission microscope has been used to search for high-energy proton induced irradiation damage of a *W* surface. The instrument was used with a magnification of about 10^6 and a resolution of about 20 A. No damage was observed *under the conditions of the experiment.* It should be emphasized, however, that, because of the experimental limitations, the lack of a positive observation does not necessarily imply that no damage occurred. An interesting side effect which at first was incorrectly attributed to irradiation damage has been observed and will be discussed.

* Research supported by a U. S. Atomic Energy Commission contract

B10. Radiation Damage in Bismuth. R. R. COLTMAN, T. H. BLEWITT, AND C. E. KLABUNDE, *Oak Ridge National Laboratory.**—Polycrystalline and single crystals of bismuth have been bombarded in the ORNL Graphite Reactor at temperatures ranging from 4°K to 20°K. The effect of dose, crystal orientation, and annealing temperatures on the electrical properties were studied. The results of these measurements suggests that the induced resistivity results from a decrease in the mean free path of the current carriers rather than a change in carrier concentration and verifies the fact that the magnitude of the radiation induced resistivity is inversely pro-

portional to the effective current carrier concentration. The 4°K bombardments were of particular interest in the light of Seeger's suggestion that the low-temperature annealing associated with radiation damage arose from a micro-recrystallization similar in character to that observed by Hilsch and co-workers on annealing metals deposited at 4°K. Neutron bombarded bismuth and Bi−0.1% U^{235}, however, failed to show any evidence of the superconducting state reported by Hilsch and co-workers in as-deposited bismuth. In the U^{235} doped bismuth, the fission-fragment damage increased the effective dose, resulting in overlap of the damaged regions. This evidence thus suggests that bismuth irradiated at 4°K does not bear a one-to-one correspondence to amorphous bismuth film deposed at 4°K.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

Invited Paper

B11. Radioactive Formation of Defects in Solids. J. LAMBE, *Ford Motor Company.* (30 min.)

MONDAY MORNING AT 10:00

Auditorium, Rackham Memorial Building

(H. BROOKS presiding)

Invited Papers

BA1. Anisotropic Superexchange Interaction and Weak Ferromagnetism. T. MORIYA, *Bell Telephone Laboratories.* (30 min.)

BA2. Problem of Reconciliation of Ferromagnetism and Superconductivity. H. SUHL, *Bell Telephone Laboratories.* (30 min.)

Magnetism: Theory

BA3. Theory of the Magnetization Curve of a Heisenberg Ferromagnet.* R. BROUT AND H. HAKEN, *Cornell University.*—An attempt is made to formulate a consistent approximate theory of the Heisenberg ferromagnet ($V=\Sigma v_{ij}S_i\cdot S_j$) which is presumably a good high-density approximation. The aim is to formulate a theory which passes continuously from the low-temperature spin-wave region to the high-temperature "classical" or Curie-Weiss region. This is done in the random-phase approximation as supplemented by the separate sphericalization of the transverse and longitudinal sum rules.[1] The result leads to a temperature-dependent spin-wave spectrum and a set of transverse excitations which are the usual spin waves at low T and become the classical spherical model normal modes at the Curie point. The longitudinal modes are always classical. For low T, the spin-wave spectrum is modified according to $\omega(q;T)=\omega(q;0)M(T)/M(0)$ where $M(T)$ is the magnetization at temperature T.

* Supported in part by the Office of Naval Research.
[1] This has been done for the Ising model by R. Brout (to be published).

BA4. Critical Concentration for the Existence of Ferromagnetism in Dilute Alloys.* M. COOPERSMITH AND R. BROUT, *Cornell University.*—By use of a theory developed in footnote,[1] we have obtained estimates of the least concentration needed to support ferromagnetism in a dilute alloy of nearest neighbor exchange-coupled spins. Diagrams have been summed so as to include all terms up to $0(x^3)$ for sc and bcc lattices, and up to $0(x^4)$ for fcc lattices. We find for these three lattices, respectively, the following results: $x_0Z=1.29,\ 1.39,\ 1.36$, where x_0 is the critical concentration and Z is the number of nearest neighbors. These results are in good accord with experiment.

* Supported in part by the Office of Naval Research.
[1] R. Brout, Phys. Rev. 115, 824 (1959).

BA5. Anisotropy Energy and Remanent Magnetization of a Frozen Boltzmann Distribution of Stoner-Wohlfarth Particles. FORREST WEST, *Texas Instruments Incorporated.*—When a specimen composed of N noninteracting ferromagnetic particles with anisotropy energy of the form $U=K\sin^2\theta$; e.g., Stoner-Wohlfarth particles, is quenched in the presence of a saturating magnetic field, the particles may be assumed to be frozen into a Boltzmann distribution. The bulk anisotropy energy E of such a distribution has been calculated and found to be of the uniaxial form $E(\phi,a)=A(a)+B(a)\sin^2\phi$; where ϕ is the angle between the quenching field direction (bulk anisotropy axis) and the saturation magnetization vector $\mathbf{M}_s$; $a=K/kT_0$; T_0 is the temperature at which the distribution is frozen; and k is the Boltzmann constant. Expressions for $A(a)$ and $B(a)$ have been derived in terms of the tabulated function $y(x)=\exp(-x^2)\int_0^x \exp(t^2)dt$. Expressions for $m_{11}(a)$ and $m_{\perp}(a)$, the remanent magnetizations parallel and normal to the anisotropy axis, as well as $C(a)$, the magnetic specific heat of the distribution, have also been derived in terms of $y(x)$. Accurately calculated curves for $A(a)$, $B(a)$, $m_{11}(a)$, $m_{\perp}(a)$ and $C(a)$ for the range $0.01\leqslant a\leqslant 100$ are presented. Applications of some of these results to paramagnetic and superparamagnetic particles are also discussed.

BA6. Magnetic Properties of Au-Mn Alloys. HIROSHI SATO, *Ford Motor Scientific Laboratory.*—Au-Mn alloys show magnetic behavior which depends upon the various types of superlattice existing in this system. The analysis of magnetic properties of these compounds revealed the possibility that the magnetic dipole interaction is responsible for the cooperative spin alignment of the system. For example, in both Au_4Mn and Au_2Mn, the Mn atoms form body-centered tetragonal lattices with c/a ratio of 0.62 and 2.60, respectively. Although the first- and the second-neighbor distance between Mn atoms for these two compounds are practically the same, the former is ferromagnetic but the latter is antiferromagnetic (or metamagnetic). The first-neighbor distance corresponds to the ferromagnetic interaction range of Mn atoms, but geometrically this alone cannot cause any cooperative alignment of spins. The second-neighbor distance, on the other hand, is too long to expect any appreciable interaction. How-

ever, it is proved that the existence of a minor interaction between the second neighbors is sufficient to produce the expected cooperative phenomena. The magnitude of such an interaction is found to be of the same order as the magnetic dipole interaction. Furthermore, such magnetic dipole interactions can explain the difference of the magnetic behavior of Au_2Mn and Au_4Mn.

BA7. High-Temperature Magnetic Susceptibility of the Heisenberg Model with First- and Second-Neighbor Interactions. P. J. WOJTOWICZ AND R. I. JOSEPH,* *RCA Laboratories.* --Several recent theoretical and experimental investigations have demonstrated the importance of the second-neighbor exchange interaction in certain antiferromagnetic compounds. We have therefore undertaken to derive the high-temperature susceptibility of the Heisenberg model including first- *and* second-neighbor interactions. Following the formal expansion method of Rushbrooke and Wood,[1] the susceptibility is obtained as a power series in the reciprocal temperature, the coefficients being computed exactly for general lattices and arbitrary spins. However, a new and simple procedure has been discovered which eliminates the considerable labor required by the formal technique. Two theorems have been deduced which permit the straightforward computation of those terms introduced by the inclusion of the second-neighbor interaction from a knowledge of the Rushbrooke and Wood result for first neighbors alone. The procedure is illustrated for the case of the high-temperature susceptibility. The application to other thermodynamic properties of Heisenberg and Ising models with first-, second-, $\cdots$, nth-neighbor interactions will be indicated.

* Present address: Department of Physics, Harvard University.
[1] G. S. Rushbrooke and P. J. Wood, J. Mol. Phys. 1, 257 (1958).

BA8. Domain Wall Energies and Entropies for the Ising Model at 0°K. JOHN W. CAHN, *General Electric Research Laboratory,* AND RYOICHI KIKUCHI, *Hughes Aircraft Company.* —The energy and entropy of domain walls at absolute zero in a number of two- and three-dimensional structures are computed for the Ising model as a function of orientation and compared with results of computations using various approximations. It is found that the Bragg-Williams approximation gives a poor estimate of surface entropy even at absolute zero. However, the pair approximation is found to be quite good at low temperatures, especially for structures of higher coordination.

BA9. Generation of Phonons by Means of High-Power Ferromagnetic Resonance Experiments. ERNST SCHLÖMANN, *Research Division, Raytheon Company.*—It has been pointed out by Kittel[1] that the magnetoelastic energy of ferromagnets leads to a coupling between spinwaves and elastic vibrations. Because of this coupling the normal modes are not purely magnetic or purely elastic, but contain admixtures of both excitations, the mixing being strongest when the unperturbed waves have the same frequency and wavelength. According to Suhl's[2] theory, spinwaves of a conveniently short wavelength are excited in high-power ferromagnetic resonance experiments. Under suitable conditions (of frequency, dc field, and sample shape) the potentially unstable modes contain appreciable admixtures of elastic excitation. The magnetoelastic coupling increases the maximum precession angle of the uniform mode, the effect being largest when z-directed spinwaves have the same frequency and wavelength as transverse elastic waves. Even under these conditions, however, the fractional increase of the maximum precession angle is expected to be only of the order of a few percent because waves propagating under a finite angle to the dc magnetic field become unstable before the z-directed waves (containing large elastic admixtures) do.

[1] C. Kittel, Phys. Rev. 110, 836 (1958).
[2] H. Suhl, J. Phys. Chem. Solids 1, 209 (1957).

MONDAY MORNING AT 10:00

Auditorium, Engineering Society

(A. C. BEER presiding)

Invited Paper

C1. Galvanomagnetic Effects in Indium Antimonide and Indium Arsenide. R. J. SLADEK, *Westinghouse Research Laboratories.* (30 min.)

Transport Properties

C2. (Abstract withdrawn.)

C3. De Haas-van Alphen Oscillations in Magnesium.* W. L. GORDON, A. S. JOSEPH, AND T. G. ECK, *Case Institute of Technology.*—De Haas-van Alphen oscillations in the magnetic susceptibility of single crystals of magnesium have been observed in magnetic fields up to 17 kgauss using a null deflection torsion balance. The dependence of the periods and amplitudes of these oscillations on angle between magnetic field and hexagonal axis of the crystal was obtained for several orientations of crystalline axes relative to a vertical suspension axis at temperatures from 2.3°K to 4.2°K. These data are in agreement with the few periods mentioned by other investigators[1,2] but are not consistent with a simple ellipsoidal description of the detail of the Fermi surface. Comparison will be made with current theories of the Fermi surface.

* Supported in part by the Research Corporation, the U. S. Atomic Energy Commission and the Air Force Office of Scientific Research.
[1] Verkin, Dmitrenko, and Mikhailov, Doklady Akad. Nauk S.S.S.R. 101, 233 (1955).
[2] D. Shoenberg, *Progress in Low Temperature Physics,* edited by C. J. Gorter (North-Holland Publishing Company, Amsterdam, 1957), Vol. II, Chap. VIII.

C4. Theory of Fuchs' Size Effect with Pure Specular Reflection. P. J. PRICE, *IBM, Watson Laboratory.*—For a solid with anisotropic electron energy surfaces, the electrical conductivity should depend on a lateral dimension, if the latter is not large compared to the bulk mean free path, even for pure specular reflection of the electrons at the boundary. For pure specular reflection, the conductivity of a thin single crystal should be changed by a factor which *tends to a nonzero limit* when the thickness is small compared to the applicable mean free path, with the limiting value depending on the degree of anisotropy and on the orientation.[1] The predicted behavior has been confirmed[2] for bismuth single crystals, at 4.2°K, with large bulk mean free paths. The theory of the effect, in terms of the generalized mean free path concept,[3] will be presented. The Hall effect and magnetoconductivity[2] will be treated.

[1] F. S. Ham and D. Mattis, IBM Journal (to be published); P. J. Price, IBM Journal (to be published).
[2] A. N. Friedman and S. H. Koenig, IBM Journal (to be published), and abstract C5.
[3] P. J. Price, IBM Journal **2**, 200 (1958).

C5. Size Effect for Conduction in Thin Bismuth Crystals. A. N. FRIEDMAN, *Columbia University and IBM, Watson Laboratory,* AND S. H. KOENIG, *IBM, Watson Laboratory.*—The electrical conductivity σ, Hall constant R_H, and magnetoresistance have been measured at liquid helium temperatures for thin single crystals of bismuth of varying orientation, and lateral dimension ($\sim$0.2–5.0 mm) of the order of the electron mean free path. The Hall data was taken with the magnetic field parallel to the thin direction. Both σ and R_H, as a function of thickness, level off to a "saturation" value in the thin limit. The existence of this saturation, the magnitude of which is dependent upon the crystallographic orientation relative to the sample geometry, indicates that the surface reflection of the carriers is specular.[1] The results, when compared with theory, are consistent with current ideas regarding the structure of the conduction band,[2] if the contribution of the holes to the conductivity is assumed negligible. Specific results for the galvonomagnetic effects, mean free path, and scattering time time will be presented.

[1] F. S. Ham and D. Mattis, IBM Journal (to be published); P. J. Price, IBM Journal (to be published), and abstract C4, this issue.
[2] See, e.g., G. E. Smith, Phys. Rev. **115**, 1561 (1959).

C6. Effect of Electron-Electron Scattering on the Wiedemann-Franz Ratio of an Electron Gas. ROBERT W. KEYES, *Westinghouse Research Laboratory.*—Electron-electron (*e-e*) collisions can degrade a thermal current, as in a monatomic gas, but can only indirectly assist the degradation of an electric current. This is because momentum is conserved in an *e-e* collision, but energy flow vector is not. Therefore the Wiedemann-Franz ratio $w \equiv (\kappa/\sigma T)(e/k)^2$, is decreased by *e-e* scattering. The calculations of Spitzer and Härm[1] show that *e-e* collisions reduce w from 4, the value given by the usual theory, to 1.622 in the case of the classical fully ionized gas. An approximate theory of the effect of *e-e* collisions on w for semiconductors, in which the scattering mechanisms are more complicated, can be formulated by the relaxation time method previously employed by the author.[2] The application of these results to the theory of thermoelectric devices will be discussed.

[1] L. Spitzer and R. Härm, Phys. Rev. **89**, 977 (1953).
[2] R. W. Keyes, Bull. Am. Phys. Soc. **2**, 313 (1957); J. Phys. Chem. Solids **6**, 1 (1958).

C7. Hall Effect, Magnetoresistance, and the Fermi Surface in Single Crystals of High Purity Copper. J. E. KUNZLER AND J. R. KLAUDER, *Bell Telephone Laboratories.*—Hall effect and magnetoresistance measurements are in progress on high purity copper ($R_{273°K}/R_{4.2°K}>4000$) at magnetic fields as large as 18 kgauss. The high field Hall constant is not isotropic and is at least 50% higher in some orientations than in others. The magnitude of the Hall constant in crystal orientations showing the largest effect is greater than would be expected for one free electron per atom. The magnetoresistance has an even greater anisotropy, In certain crystal directions and at high fields, the magnetoresistance saturates with $\Delta\rho/\rho_{H=0}<1$ while in other orientations it varies as H^2 and $\Delta\rho/\rho_{H=0}$ is >500. These large variations indicate there are regions in which the Fermi surface intersects the boundary of the first Brillouin zone. Studies of anomalous skin effect[1] have independently lead to the same conclusion. A study is being made of a theoretical shape for the Fermi surface consistent with the present experimental results. The data and progress in its interpretation will be discussed.

[1] A. B. Pippard, Phil Trans. Roy. Soc. (London) **A250**, 325 (1957).

C8. Optical Properties of Copper. S. ROBERTS, *General Electric Research Laboratory.*—Optical properties of solid copper have been measured in a wavelength range from 0.365 to 2.5 μ and at temperatures 90°, 300°, and 500°K. Annealed and electropolished specimens were used. Measurements were done in a vacuum of about 2×10^{-6} mm (Hg), and it was observed that the oxide film which normally forms on copper upon exposure to air could be removed by heating in vacuum to a temperature of 500°K. In the wavelength range below 0.6 μ the data confirm the well-known facts relating to a threshold for interband electronic transitions. At longer wavelengths the optical properties are determined almost entirely by free electrons. Deviations from simple theory are partly explained by the anomalous skin effect, and it is concluded that the electronic collisions at the metal surface are diffuse. However, it is shown that the anomalous skin effect is not sufficient to explain the observed deviations and that a more complete interpretation ought to consider the nonspherical nature of the Fermi surface and variation of the relaxation time over this surface.

C9. Faraday Effect in Aluminum.* EDWARD A. STERN, *University of Maryland.*—By measuring the rotation of the plane of polarization of light after reflecting from a metal surface in a magnetic field, one can determine an effective mass of the conduction electrons.[1] The effective mass for aluminum determined this way is about 1.5 times the free-electron value. This effective mass will be compared with measurements on Al using other techniques. The possible information that this technique gives on the band structure of Al will be discussed.

* Research supported by the National Security Agency.
[1] E. A. Stern and R. D. Myers, Bull. Am. Phys. Soc. Ser II, **3**, 416 (1958).

C10. Thermoelectric Power of Dilute Indium Alloys. E. I. SALKOVITZ AND E. W. KAMMER, *U. S. Naval Research Laboratory.*—Indium is trivalent and has a face-centered tetragonal structure. From a band theory point of view electron overlaps are expected, and Reitz has already proposed such a model. The degree of overlap can be grossly effected by changing the electron concentration via alloying with divalent cadmium on the one hand and quadrivalent tin or lead on the other. Thermoelectric power measurements have been made on such alloys with compositions ranging up to the solubility limits. These measurements have been made at 78°K, 273°K, and in some cases at 350°K. In addition, x-ray lattice parameter measurements have been made. Cadmium additions cause the thermoelectric power to decrease, and there is confirmation of a sluggish phase transformation. Additions of lead or tin produce maxima and minima in the thermoelectric power versus composition curve which may be interpreted in terms of the overlap theory.

C11. Additional Experiments on the Thermoelectric Power of Magnesium Ternary Alloys. E. W. KAMMER AND E. I. SALKOVITZ, *U. S. Naval Research Laboratory.*—An investigation

of the electron transport properties of dilute magnesium binary alloys demonstrated that the magnitude and sign of such properties were dependent on the electron concentration of these alloys. Then, by adding equal amounts of monovalent silver and trivalent indium to magnesium, a series of ternaries were obtained of relatively constant electron concentration. The thermoelectric power for these alloys behaved similarly to a previously studied MgCd series. Extending this work, new results have now been obtained on magnesium ternaries, containing both silver and quadrivalent tin, which behave in such a manner that the thermoelectricity curve is similar to that of the previously studied Mg-In binary alloys. X-ray lattice parameter measurements have been made of the binary and ternary series and comparisons will be made.

C12. High-Temperature Electrical Resistivity Measurements in Beta-Brass Type Alloys. F. ROTHWARF, *Frankford Arsenal*, AND L. MULDAWER, *Temple University*.—The disordering in AgCd and Au modified AgCd alloys has been observed by means of at-temperature measurements of electrical resistivity. As expected the critical temperature for disordering rises for increasing substitution of Au for Ag. In addition, there are deviations from linearity observed for either ordered or disordered alloys at temperatures in excess of about two-thirds the melting temperature. These effects have been observed in AuCd, AuZn, CuZn, etc. These deviations will be discussed in terms of vacancies and they will be correlated with results of quenching experiments.

MONDAY MORNING AT 10:00

WSU Community Arts Auditorium

(H. P. R. FREDERIKSE presiding)

Invited Paper

CA1. Photoemission of Electrons from Metals into Cadmium Sulfide. R. WILLIAMS, *RCA Laboratories*. (30 min.)

Compound Semiconductors, I

CA2. Band Structure and Electrical Properties of GaAs. H. EHRENREICH AND D. J. OLECHNA, *General Electric Research Laboratory*.—A consistent picture concerning the band structure of GaAs is now beginning to emerge from the experimental results and preliminary interpretation given by workers at different laboratories. The conduction band edge is at [000] with a mass of about $m_{cl}=0.078m_e$. Another set of minima in [111] directions lie about 0.25 ev above the edge, and a third set in [100] directions probably lie 0.5 ev above the edge. The valence bands are similar to those in germanium with masses of about 0.65, 0.11, and 0.19 for the heavy mass, light mass, and split-off bands, respectively, and a spin-orbit splitting of 0.33 ev. With this information, the transport properties of n-type GaAs may be explained in the following manner. The mobility above room temperature is quantitatively determined by polar scattering. The limiting mobility at 300°K is estimated to be 8000–10 000 cm²/v-sec. The [111] minima contribute appreciably to the mobility and Hall coefficient R_H between 500 and 1000°K. The maximum in R_H at elevated temperatures has been previously explained in terms of such a band structure by Gray and Ehrenreich. The observed increase of resistance with pressure in n-type material can be explained quantitatively in terms of an increase of band gap and hence of m_{cl} at pressures below about 10^3 kg/cm² and qualitatively at higher pressures.

CA3. Excitons and the Absorption Edge of CdS. D. G. THOMAS, J. J. HOPFIELD, AND M. POWER, *Bell Telephone Laboratories*.—Measurements of the absorption coefficient between 10 and 300 cm^{-1} have been made with crystals of CdS in polarized light between 20° and 300°K at wavelengths near 5000 A. Analysis of the results near 70°K shows that the absorption is in agreement with that calculated for a process involving the simultaneous creation of an exciton and the absorption of a longitudinal optical phonon of energy 0.038 ev, both particles having a small wave vector. The energies and oscillator strengths of the excitons and the phonon energy are known from independent experiments. The one remaining adjustable parameter can be calculated correctly to within an order of magnitude. No evidence could be found for non-vertical transitions. It is concluded that the conduction and valence band valleys have the same wave vector and that most probably these occur at the center of the Brillouin zone.

CA4. Some Electrical, Optical, and Structural Properties of CdS,Se Solid Solutions.* SHAUN DEVLIN AND L. R. SHIOZAWA, *Clevite Corporation*.—CdS and CdSe both have the wurtzite structure with $a_0=4.136$ A, 4.292 A, respectively. They are completely miscible throughout the entire range of composition with no trace of superlattice formation. The lattice constant of the solid solutions satisfy Vegard's law quite well. The primary optical absorption was measured. The variation of the optical energy gap with composition is concave upward. The Hall effect and conductivity of a number of compositions has been measured from 80°K to 750°K. The electron mobility of the solid solution is generally lower than in either pure compound. The electron mobility of $CdS_{0.5}S_{0.5}$ is 250 cm²/v-sec at room temperature. These measurements will be compared with the work of Vitrikhovskii and Mizetskaya.[1]

* Supported by the Wright Air Development Center, U. S. Air Force.

[1] N. I. Vitrikhovskii and I. B. Mizetskaya, Soviet Phys.—Solid State **1**, 358 (1959).

CA5. Energy Gap of SiC, Polytype 4*H*. LYLE PATRICK, D. R. HAMILTON, AND W. J. CHOYKE, *Westinghouse Research Laboratories*.—Earlier measurements of the energy gap[1] of hexagonal SiC were made on crystals of the most common polytype, called polytype 6*H* in the notation of Ramsdell. We have now made similar measurements on crystals of SiC polytype 4*H*. The 4*H* specimens were obtained by grinding away the 6*H* portions of some crystals of mixed 6*H* and 4*H* polytypes. Preliminary measurements of the absorption and photoluminescence spectra indicate that the energy gap of 4*H* SiC is approximately 0.3 ev greater than that of 6*H*. The optical transitions are indirect in both polytypes. An analysis of the absorption data will be presented.

[1] W. J. Choyke and Lyle Patrick, Phys. Rev. **105**, 1721 (1957).

CA6. Effects of Si in GaAs. J. M. WHELAN, J. D. STRUTHERS, AND J. A. DITZENBERGER, *Bell Telephone Laboratories.*—The negative Hall coefficient of Si doped GaAs grown from the melt is inversely proportional to the Si content for concentrations less than 1×10^{18} atoms cm^{-3}. For Si concentrations between 0.6 and 3×10^{19} atoms cm^{-3}, the Hall coefficient is essentially independent of concentration although the solubility of Si in GaAs has been reported to be $1-2\times10^{20}$ atoms cm^{-3}.[1,2] Si atoms located on Ga or As lattice sites act as either donors or acceptors, respectively. The preceding data are consistent with the fraction of total Si on either lattice site varying as a function of the Fermi level, as proposed by Longini and Greene for an amphoteric impurity.[3] The applicability of this model is further supported by Hall data for GaAs specimens containing Si and either normal donor or acceptor impurities.

[1] C. Kolm, S. A. Kulin, and B. L. Averbach, Phys. Rev. **108**, 935 (1957).
[2] E. Arnold, J. Black, and S. Weissberger, Electrochem. Soc. Meeting, October 1958.
[3] R. L. Longini and R. F. Greene, Phys. Rev. **102**, 992 (1956).

CA7. Recombination Centers in Indium Antimonide.* R. A. LAFF AND H. Y. FAN *Purdue University.*—The lifetimes of holes and electrons have been determined from photoconductivity and PEM measurements in the range 200°K–15°K for several p-type single crystals of InSb. In the extrinsic range, the data can be interpreted on the basis of a single set of trapping centers with an energy level 0.05–0.06 ev above the valence band and with capture cross sections 6.5×10^{-13} cm^2 and 4×10^{-17} cm^2 for electrons and holes, respectively. In the freezeout range, holes are assumed to be in equilibrium with bound holes on acceptors. From the temperature variation of Hall coefficient, the trap concentration was estimated to be $\sim10^{14}$ cm^{-3}. The large cross-section ratio indicates that the traps are donors. Heat treatment and quenching, with or without addition of copper, increase the hole concentration. Irradiation with 4.5-Mev electrons at 0°C was found to reduce the hole concentration and introduce trapping centers having about the same characteristics as found in normal samples. A flux of 1.8×10^{15} cm^{-2} of electrons reduced the electron lifetime by an order of magnitude, while the hole lifetime increased slightly. It appears that the trapping centers in normal InSb are in nature similar to the trapping defects introduced by bombardment.

* Work supported by Office of Naval Research contract.

CA8. Influence of Inhomogeneities on the Galvanomagnetic Effects in n-type InSb.* R. T. BATE, R. K. WILLARDSON, AND A. C. BEER, *Battelle Memorial Institute.*—When single crystals of high purity InSb are grown in the ⟨111⟩ direction, anistropic segregation of residual donor impurities occurs. This segregation can produce longitudinal and radial gradients in the extrinsic electron concentration in the crystal. Changes of an order of magnitude in carrier concentration from the center axis to the surface of a crystal have been observed. If a sample is cut from an inhomogeneous region in the crystal and current is directed through it in the presence of a strong transverse magnetic field, the carrier gradient may superimpose circulating currents on the drift current. These currents markedly influence the observed galvanomagnetic effects in the extrinsic temperature range. For example, the absolute value of the Hall coefficient was observed to increase approximately as log$H$ in the strong field region, and to be as much as twice as large at 20 kgauss as its weak field value. The magnetoresistance is especially sensitive to inhomogeneities. For an inhomogeneous sample at a particular magnetic field, $\Delta\rho/\rho_0$ may be as much as 100 times larger than that for a homogeneous sample. Negative magnetoresistance has also been observed at room temperature in inhomogeneous samples.

* Supported by the Air Force Office of Scientific Research.

CA9. Transport Effects in n-type InSb and n-type HgSe. THEODORE C. HARMAN, *Lincoln Laboratory,** *MIT.*—Transport theory has been formulated for band models of $\epsilon=\hbar^2k^2/2m$ and the $\epsilon(k)$ calculated by Kane,[1] exact statistics, a relaxation time given by $\tau=\tau_0\epsilon^{r-\frac{1}{2}}$, and any magnetic field below the quantum region. Both band models predict (1) magnetoresistance for Corbino disk geometry is approximately $(\mu H)^2$, (2) the Corbino magneto-Seebeck effect vs μH is a strong function of the scattering parameter r and a weak function of the statistics parameter η, and (3) the zero magnetic field thermoelectric power is a weak function of the scattering parameter r and a strong function of the statistics parameter η. Thus, measurement of the Corbino magneto-Seebeck effect versus H, the thermoelectric power, and mobility enables r and η to be determined. Knowledge of r, η, mobility and carrier concentration allow m and τ to be calculated at the Fermi energy. Results of measurements of Hall coefficient, electrical resistivity, thermoelectric power, Corbino magnetoresistance, and the Corbino magneto-Seebeck effect for n-type single crystals of both HgSe and InSb in the 5×10^{17}/cm^3 to 5×10^{18}/cm^3 impurity concentration range will be compared with theory.

[1] E. Kane, J. Phys. Chem. Solids **1**, 249 (1957).
* Operated by MIT with support of U. S. Army, Navy, Air Force.

CA10. Magnetic-Field Dependence of the Hall Coefficient in p-type PbTe. R. S. ALLGAIER AND J. R. BURKE, JR., *U. S. Naval Ordnance Laboratory.*—We have made precise measurements at room temperature and 77°K of the Hall coefficient R as a function of $\mu_H H$ (the product of Hall mobility and magnetic field strength) in single crystals of p-type PbTe. In a sample at 77°K for which the current and magnetic field were along cubic axes of the crystal, R gradually increases for field values above $\mu_H H=3\times10^7$ cm^2-gauss/v-sec, and at $\mu_H H=2\times10^8$ is 10% higher than the weak-field value of 2.30 cm^3/coulomb. This result conforms quite closely to the Bullis and Krag Hall-coefficient theory[1] for the ⟨111⟩ multivalley model with a constant scattering time and the anisotropy factor $K=3.5$. Better agreement with the value $K=4.2$ derived from weak-field magnetoresistance measurements at 77°K[2] is obtained if the weak-field portions of the theoretical curves are raised about 1½% to take into account the energy dependence of the scattering time under the conditions of highly degenerate statistics which are appropriate for these samples. Room temperature measurements of R, which were confined to the weak-field region, reveal no dependence on the magnetic field strength.

[1] W. M. Bullis and W. E. Krag, Phys. Rev. **101**, 580 (1956).
[2] R. S. Allgaier (unpublished).

CA11. Relations between the Masses of the Positively and Negatively Charged Ions in Crystals. N. EFREMOV, *600 W. 142nd Street, New York, New York.*—In iron monosulphide FeS, according to the law of constant proportions, the mass ratio is Fe:S=55.85:32.06. This example (it is a classical one) is being cited in manuals. But curiously enough these relations are never encountered in the composition of natural crystals of iron monosulfide—pyrrhotite. As a rule, there is a surplus of sulfur. Applying to this case the rule of simple small mass relations, we can calculate the most probable proportions between the mass of iron and that of sulphur in pyrrhotite crystals: Fe:S=3:2. Consequently, the theoretically calculated formula of pyrrhotite should be Fe_6S_7. And actually this is the formula of the most abundant pyrrhotites. These phenomena (the composition of pyrrhotites, magnetites etc.) may be explained as results of the tendency to the equilibrium between electronegative masses and electropositive masses in crystals. Therfore in the composition of pyrrhotites, besides the bivalent Fe ions there are also trivalent Fe ions which bind the surplus of sulfur ions.[1]

[1] N. V. Belov, Acad. Sci. U.S.S.R., **2**, 7–13 (1953).

MONDAY MORNING AT 10:00

WSU McGregor Memorial

Conference Center Room L

(J. S. KOEHLER presiding)

Internal Friction and Diffusion

D1. Broadening of an Internal Friction Peak due to a Gaussian Distribution in ln τ. B. S. BERRY AND A. S. NOWICK, *IBM Yorktown Research Center.*—The widths of internal friction peaks in metals and alloys invariably exceed the value predicted by the use of a discrete relaxation time. In an early paper, Wagner[1] calculated the shape of dielectric loss peaks when a distribution of relaxation times about a mean value $\langle\tau\rangle_{Av}$ was taken in the Gaussian form $\exp[-b^2(\ln\tau/\bar{\tau})^2]$. The purpose of the present work is to extend Wagner's theory and to apply it to anelastic phenomena. The results are as follows: (1) The dependence of the width of an internal friction peak on the distribution parameter b^{-1} is obtained. (2) It is noted that the derived internal friction peaks may be fitted rather well by the equations relating to a discrete relaxation time with the substitution of an appropriately chosen "false" activation energy which is lower than the true activation energy. (3) It is shown that the distribution in ln τ may be resolved into a distribution in the activation energy and one in the frequency factor; further, that the quantity b^{-1} varies as $AT^{-1}+B$ where A is related to the distribution in activation energy and B to that in the frequency factor. Application of these results will be discussed.

[1] K. W. Wagner, Ann. Physik **40**, 817 (1913).

D2. Internal Friction of Copper Following Deformation at 78°K. D. O. THOMPSON AND V. K. PARÉ, *Oak Ridge National Laboratory.**—In an attempt to find stress relaxation internal friction peaks in copper which can be attributed to nonspherically symmetric defects,[1] a technique has been developed which permits sample deformation in the measuring apparatus. The most important feature of the technique is the fact that the internal friction and Young's modulus can be measured during the first warmup following deformation at 78°K. Results of the first set of experiments will be given. It is found that several peaks occur in the temperature range from 190°K to about 270°K at a measuring frequency of 11 kc. For the most part, they appear to be amenable to an analysis into single relaxation peaks with reasonable values for the various parameters. There is, however, a marked difference among the peaks in their resistance to annealing in the range of 0°C to 150°C. On this basis, a working hypothesis has been adopted which states that the observed annealing differences can be attributed to defects in the lattice as opposed to those defects which are trapped by dislocations. Some correlation of these results with radiation damage experiments seems to be present.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] R. R. Hasiguti and S. Okuda, Proc. Japan Acad. **35**, 284 (1959).

D3. Stress Induced Ordering in Silver Alloys.* T. J. TURNER AND G. P. WILLIAMS, JR., *Wake Forest College.*—Internal friction studies have been made on a number of alloys of silver with elements immediately following it in the periodic table. AgCd, AgIn, AgSn, and AgSb were studied utilizing an inverted torsion pendulum and an elastic-after-effect apparatus of the conventional type. In each case the polycrystalline samples were alpha phase (fcc) with a maximum solute concentration. An Arrhenius plot of relaxation time, determined from Zener peak positions with the torsion pendulum data and inflection points from elastic-after-effect data, yield activation energies of approximately 34 kcal/mole for AgCd and approximately 28 kcal/mole for AgIn. The results will be discussed and compared with extensive diffusion data obtained by Schoen on the same systems.[1]

* Supported in part by the U. S. Atomic Energy Commission.
[1] A. H. Schoen, thesis, University of Illinois (1958).

D4. Internal Friction in Silver-Gold.* G. P. WILLIAMS, JR., AND T. J. TURNER, *Wake Forest College.*—Since the solid solution of AgAu exists over the entire range of concentrations it is not subject to the limitations inherent in the Ag-alloy series discussed in the preceding paper. Previous work in this Laboratory on the study of stress induced ordering in the AgAu system has indicated the desirability of extending the measurements to additional alloy concentrations. A curve is presented which exhibits the behavior of the relaxation strength as a function of concentration, with the maximum slightly displaced to the Au-rich side. The grain boundary peak has also been investigated. Activation energies for various concentrations have been determined and comparison is made with extensive tracer diffusion data for the same system recently obtained by W. Mallard, R. Bass, A. Gardner, and L. Slifkin.[1]

* Supported in part by the U. S. Atomic Energy Commission.
[1] Private communication.

D5. Mechanical Relaxation Peaks in Prestrained Polycrystalline Molybdenum and Tantalum.* R. H. CHAMBERS AND J. SCHULTZ, *General Atomic.*†—Measurements have been made of the internal friction and Young's modulus in prestrained polycrystalline molybdenum and tantalum near 15 kc/sec as a function of temperature from 60°K to 380°K. Two peaks in the internal friction vs temperature plot appear in this temperature range for the prestrained molybdenum: one at 110°K and the other at 350°K. One peak appears in the prestrained tantalum at 170°K. The peaks in both metals disappear on high temperature anneal and increase in magnitude with increased amounts of prestrain. The origin of these strain-induced peaks is discussed in terms of a dislocation relaxation mechanism.

* This research was supported by the U. S. Atomic Energy Commission.
† John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.

D6. Monte Carlo Annealing Experiments.* J. R. BEELER, JR., AND LEO VON GOTTFRIED, *General Electric Company.*—We have used Monte Carlo experiments (on an IBM 704) to study the spatial detail of annealing caused by the diffusion of a single vacancy in a two-dimensional binary lattice. The interaction among the first-, second-, and third-neighbor sites about the current position of the vacancy was used to determine the Boltzmann factor for each possible jump direction. The jump direction was then selected for the cumulative distribution function derived from these Boltzmann factors. The diffusion trajectory appears to proceed through three stages of development. Initially the vacancy follows a filamentary path. In the intermediate stage the path takes the form of a chain of reentrant loops and in the third stage terminates in tightly localized oscillation among a few principal sites. Most of the annealing activity takes place during the intermediate stage.

Longitudinal and transverse diffusion lengths, and an exhaustion jump number, which characterize this behavior, will be presented. There appears to be positive correlation between the short range order in the first- and second-neighbor sites about the vacancy and the onset of the terminating stage in which the annealing capacity of the vacancy disappears.

* Work sone under the auspices of the U. S. Atomic Energy Commission and the U. S. Air Force.

D7. Vacancies and Shocks in Metals. MAX SOLOW, N. L. COLEBURN, AND R. C. WILEY, *U. S. Naval Ordnance Laboratory.*—Shocks in metals give rise to many physical phenomena such as hydrodynamic behavior, hardening, etc. Since shocks move supersonically with respect to the undisturbed material, dislocations cannot directly explain these phenomena. The mechanism responsible for shock effects is the creation of vacancies by the interaction of the shock front with the dislocations, impurity atoms, grain boundaries, etc. To estimate the number of vacancies created in a metal, the equation of state of the metal is used to calculate the Rankin-Hugoniot energy supplied by the shock and the energy necessary to compress the metal adiabatically. The difference between the Hugoniot and the adiabatic energy is the energy used in entropy production; it is assumed that this dissipative process is the creation of vacancies. These calculations are made for aluminum using 0.76 ev and 0.65 ev as the activation and motion energy of a vacancy, respectively. It is shown that a number of vacancies equal to that at melting can be produced by a shock of 66 kbars. Using the Bollmann technique, aluminum foils have been polished to thinner than 400 A and dislocations observed by transmission electron microscopy. Both unshocked and shocked foils have been examined and evidence of supersaturation of vacancies in the shock material has been observed.

D8. Production of Vacancies in Pulsed Gold.* J. J. JACKSON AND J. S. KOEHLER, *University of Illinois.*—99.999% pure well-annealed 2-mil gold wires were pulse heated to temperatures in the range 650°C to 900°C for times from 5×10^{-4} sec to 20 sec. They were then quenched in a helium atmosphere the cooling curve being exponential. The time to drop halfway to 78°K was 10^{-3} sec. The high temperature was constant to ±1°K for pulse times shorter than 2×10^{-3} sec. Thee rsistance quenched is varied as $\mathrm{Re}[1-\exp(-\alpha t)]$ where t is the time at the elevated temperature, α is $B\exp[-0.95\ \mathrm{ev}/kT]$, and Re is the equilibrium resistance quenched in at that temperature. The time to produce half the equilibrium resistance increment varied from 16 msec at 800°C to 80 msec at 650°C. The additional resistance is due to lattice vacancies since the activation energy associated with the annealing of a wire pulsed to 700°C or less is that appropriate to the motion of single vacancies. From 800°C the energy ranged from an initial value of 0.69 ev to a final value of 0.80 ev. Dislocations acted as sources and sinks for vacancies. The interpretation will be discussed.

* Supported by the U. S. Army Office of Ordnance Research.

D9. Effect of Plastic Deformation on Vacancy Movement in Quenched Aluminum Crystals. J. A. PESCH AND L. J. FIEGEL, *Allis-Chalmers Manufacturing Company.*—The effect of plastic deformation on the movement of vacancies in quenched crystals of aluminum has been investigated by means of tensile tests and density measurements. The tensile stress-strain curve for an aluminum single-crystal rod quenched in water from 400°C indicated a high Young's modulus below a total strain of 6×10^{-6}. After plastic deformation of 0.3% longitudinal strain, followed by a room temperature anneal in the tensile apparatus, the Young's modulus decreased significantly. The Young's moduli of crystals quenched from 480°C and 540°C were below normal. Density measurements, before and after permanent deformation of 0.2% longitudinal strain, were made on the two crystals quenched from 480°C. Density changes of $+(3\pm0.4)\times10^{-5}$ and $+(1.5\pm0.04)\times10^{-4}$ were measured. It is suggested that further clustering of vacancies is brought about during the plastic deformation.

D10. Effect of Pressure on the Mobility of Interstitial Oxygen and Nitrogen in Vanadium.* G. W. TICHELAAR,† R. V. COLEMAN, AND D. LAZARUS, *University of Illinois.*—Measurements of anelastic relaxation as a function of pressure to 9000 atm have been made on a vanadium sample containing oxygen and nitrogen. For the temperature range 82.6°C to 97.6°C, the relaxation time due to dissolved oxygen is found to increase exponentially with pressure to a value 1.75 times the zero-pressure value. The relaxation times at low pressure are in agreement with the previous work of Powers and Doyle,[1] and give an activation energy of 28 kcal/mole. The pressure dependence can be interpreted in terms of an activation volume of 1.7 cm³/mole, about equal to the molar volume of the diffusing oxygen atoms. Relaxation times have been measured for the dissolved nitrogen at 155.8°C and 162.0°C. The activation energy is 37 kcal/mole, and the activation volume is about 1.7 cm³/mole.

* Supported in part by the U. S. Atomic Energy Commission.
† Present address: Research Laboratory, Eindhoven, Netherlands.
[1] R. W. Powers and M. V. Doyle, Acta Met. 6, 643 (1958).

MONDAY AFTERNOON AT 2:00

Lecture Hall, Institute of Arts

(J. R. PLATT presiding)

Chemical Physics

DA1. On the Nature of Rydberg Molecular Orbitals.* R. S. MULLIKEN, *University of Chicago.*—RyAO's (Rydberg atomic orbitals) have sharply defined l values but term values ry/n^{*2}, where $n^*=n-\delta$, with δ ascribable mainly to *penetration* by otherwise hydrogenic AO's into the singly charged "core." RyMO's (Rydberg molecular orbitals) should have the same characteristics except that δ must consist of penetrational (δ_{pe}) and promotional (δ_{pr}) parts, varying with interatomic distances R. As $R\to0$, some lower RyMO's become core AO's, higher ones RyAO's. At normal R values, δ_{pr} for a RyMO depends on the degree of promotion of its "ancestors" in the molecule core. Although core MO's, therefore the *penetrating parts* of RyMO's, lack well-defined l's the ancestry of any RyMO family (e.g., $n\rho\sigma$ or $n\rho\pi$) can be allocated. In N_2, the $n\rho\sigma$ ($n\geq4$) ancestors are $1\sigma_u$ (approximately σ_u1s) and $2\sigma_u$ (roughly σ_u2s), correlated as $R\to0$ with $2\rho\sigma$ and $3\rho\sigma$. Being essentially unpromoted at $R=R_e$, $1\sigma_u$ bequeaths $\delta_{pr}=1$ to all its descendants. For $4\rho\sigma$, $\delta\approx1.7$ (from $n^*\approx2.3$) is explainable by $\delta_{pr}=1$, $\delta_{pe}\approx0.7$. For $3p\pi$, $\delta\approx0.7$ ($n^*\approx2.3$) can be identified as $\delta_{pe}\approx0.7$ mainly; its only ancestor π_u2p becoming $2p\pi$ as

$R \rightarrow 0$ is unpromoted at all R. The n^*'s of RyMO's of H_2, He_2, etc., can be understood similarly and predictions made for other molecules.

* Work supported by the Office of Naval Research.

DA2. Configuration Interaction in Simple Atomic and Molecular Systems.* A. W. WEISS, *University of Chicago* (introduced by R. S. Mulliken).—A series of large-scale calculations is being made on the ground states of 2-, 3-, and 4-electron systems to determine the practicable accuracy that can be obtained with a configuration-interaction type of wave function. The form of the trial function is $\Psi = \Sigma c_i \Phi_i$, where each Φ_i is a suitably antisymmetrized product of one-electron functions. For atoms, the latter are simply the Slater-type AO's (atomic orbitals) with variable exponents. The atomic systems being investigated are He, Li, and Be, and their isoelectronic ions. Preliminary results indicate that an accuracy of at least 0.015 ev in the total energy can be expected. The completion of a multicenter linear integrals program by A. D. McLean has also made it possible to extend these calculations to the correspondng molecular systems, in which case the one-electron functions used are either Slater-type AO's on each center or primitive symmetry orbitals constructed from them. Currently under study are H_2 and LiH with the intention, in the future, of extending this work to such systems as H_2^-, H_3, H_4, HeH, etc. Further results will be presented at the meeting.

* Work supported by Office of Naval Research.

DA3. Potential Curves for H_2, He_2^{++}, He_2 and Ne_2*.* B. J. RANSIL, *University of Chicago.*—Wave functions, the corresponding total molecular energy, and orbital energies have been computed for the lowest $^1\Sigma_g^+$ states of H_2, He_2^{++}, He_2, and Ne_2 in LCAO-MO-SCF approximation utilizing an extended basis set $1a$, $2s$, $2p\sigma$ for the hydrogen and helium calculations and the set $1s$, $2s$, $2p\sigma$; $2p\pi$ for the neon calculation. Curves for both the single-determinantal and configuration-interaction approximations will be discussed. Comparisons to previous calculations and experimentally derived curves will be made providing some insight into the relation of functional accuracy to the degree of approximation employed.

* Supported in part by a grant from National Science Foundation, by Office of Ordnance Research, and by Air Force contracts.

DA4. Quantum Mechanical Study of the Interaction of Two Helium Atoms.* P. E. PHILLIPSON, *University of Chicago.*—The repulsive interaction potential $V(R)$ between two ground state helium atoms ($^1\Sigma_g^+$ state of He_2) has been computed for 30 internuclear distances R ranging from 0.5 A to infinity. The wave function employed is of the ASMO form $\psi = 1/(4!)^{\frac{1}{2}} |\sigma_g(1)\alpha(1)\sigma_g(2)\beta(2)\sigma_u(3)\alpha(3)\sigma_u(4)\beta(4)|$, where $\sigma_{g,u} = N_{g,u}[1s_a \pm 1s_b]$, and the $(1s)$ functions are of the form $(1s) = (\zeta^3/\pi)^{\frac{1}{2}} e^{-\zeta r}$. The procedure was to vary independently the effective nuclear charge ζ_g and ζ_u of the σ_g and σ_u orbitals to minimize the energy for each R. The energies obtained will be compared with recent self-consistent field calculations of He_2 by B. J. Ransil of this laboratory which employ an extended atomic orbitals basis set $1s$, $2s$, and $2p\sigma$, minimizing the energy with respect to linear variational parameters and orbital exponents. This is to be compared with simpler wave function mentioned here with nonlinear variational parameters ζ_g and ζ_u. For small R values both wave functions yield a decided improvement in the energy over previous computations. The properties of the wave functions, van der Waals attractive effects at large R and plans for a more accurate calculation will be discussed.

* Shell Oil Fellow 1958–1959; work assisted in part by Office of Naval Research.

DA5. Electron Population in CO_2 and C_2H_2.* A. D. MCLEAN, B. J. RANSIL, AND R. S. MULLIKEN, *University of Chicago.*—Electron population analyses have been carried out on the single-determinantal LCAO-MO-SCF wave functions for CO_2 and C_2H_2 computed by A. D. McLean.[1] The electronic structure of CO_2 and C_2H_2 will be discussed in terms of atomic and overlap populations,[2] including computed values of the charges on the atoms and of the extent of s-p hybridization of the C and O atoms in the various bonds. The structures of C_2H_2 and N_2 will be compared.

* Supported in part by a grant from National Science Foundation, by the Office of Ordnance Research, and by Air Force contracts.

[1] A. D. McLean, J. Chem. Phys. (to be published).
[2] R. S. Mulliken, J. Chem. Phys. **23**, 1833, 1841, 2338, 2343 (1955).

DA6. Calculations of Optical Transition Probabilities.* S. EHRENSON AND P. E. PHILLIPSON, *University of Chicago.*—Computations of oscillator strengths for atomic and simple molecular systems have been carried out by three alternative methods. These employ the dipole length, dipole velocity, and dipole acceleration operators, respectively.[1] Identical results would be obtained in all three cases for exact eigenfunctions of the ground and excited states. When approximate wave functions are used, the three approaches usually yield widely divergent values. The reason is that each method emphasizes different spatial portions of the approximate wave functions. This suggests that comparison of f values computed these three ways with each other and with empirical data gives another means of estimating the goodness of a wave function supplementing the usual energy-minimization criterion. Specifically, the $^1\Sigma_g - {}^1\Sigma_u$ transition (Lyman bands) of hydrogen is considered using two types of simple LCAO-MO wave functions. The first computation uses MO's built up from simple free-atom AO's, the second uses MO's of the same general form except that improved AO's are employed.[2] Comparisons are drawn with earlier work[3] and with empirical Lyman system transition strengths.

[1] H. A. Bethe and E. E. Salpeter, *Handbuch der Physik* (Springer-Verlag, Berlin, 1957), pp. 334–8.
[2] P. E. Phillipson and R. S. Mulliken, J. Chem. Phys. **28**, 1248 (1958).
[3] R. S. Mulliken and C. A. Rieke, Repts. Progr. Phys. **4**, 231 (1941); H. Shull, J. Chem. Phys. **20**, 18 (1952).
* Work supported by the Office of Naval Research.

DA7. An ASMO LCAO Calculation on Ethylene.* S. HUZINAGA, *University of Chicago* (introduced by R. S. Mulliken).—Electronic states of planar ethylene are calculated by the ASMO LCAO method. The molecule is regarded as a system consisting of two $2p\pi$ electrons in a Mayer-Sklar-type core potential field. The calculation is a variational one in which the orbital exponents ζ_g and ζ_u are determined separately for the *gerade* and *ungerade* molecular orbitals, respectively, by minimizing the energy of each state. The best ζ_g and ζ_u are quite different for the first excited triplet (T) and singlet (V) states, and this in turn results in a significant improvement of the theoretical value of the energy separation between the T and V states. Some discussion will be given on the validity of the variation calculation based upon the Mayer-Sklar-type Hamiltonian.

* Work supported by the Office of Naval Research.

DA8. Electronic Properties of Selected Diatomic Molecules.* S. FRAGA AND B. J. RANSIL, *University of Chicago.*—Configuration interaction has been applied to single-determinantal functions for LiH, BH, NH, HF, Li_2, Be_2, C_2, N_2, F_2, CO, BF, and LiF computed previously by Ransil.[1] The total computed molecular energies, dissociation energies, and dipole moments will be discussed and compared to available experimental data.

* Supported in part by a grant from National Science Foundation, by the Office of Ordnance Research, and by Air Force contracts.

[1] B. J. Ransil, Bull. Am. Phys. Soc. Ser. II, **4**, 174 (1959); Revs. Modern Phys., **32**, (1960).

DA9. Atomic SCF Wave Functions in Analytical Form.* C. C. J. ROOTHAAN, M. YOSHIMINE, AND S. HUZINAGA, *University of Chicago.*—Self-consistent field calculations have been carried out for a number of atoms in the first row of the periodic table. The formalism used[1] solves the variational problem of determining the orbitals without the customary approximations of neglecting off-diagonal Lagrangian multipliers. The orbitals were determined by expansion in terms of suitable basis functions, as was done recently for a number of atomic systems.[2] The calculations were performed on the Remington Rand 1103A Univac Scientific Computer at WPAFB. The input data are the orbital exponents and principal quantum numbers of the basis functions, and the numbers and symmetry species of the occupied orbitals, and certain constants specific to the electronic state. Numerical results will be discussed in some detail.

* Work supported by a grant from the National Science Foundation and by Wright Field Air Development Center.
[1] C. C. J. Roothaan, Revs. Modern Phys. (to be published).
[2] C. C. J. Roothaan, L. M. Sachs, and A. W. Weiss, Revs. Modern Phys. 32, No. 2 (1960); R. E. Watson, Tech. Rept. No. 12, Solid State and Molecular Theory Group, Massachusetts Institute of Technology (1959); A. M. Karo and L. C. Allen, J. Chem. Phys. 31, 968 (1959).

DA10. Trapped Radicals in Irradiated N-Propanol at 77°K. R. S. ALGER, T. H. ANDERSON, AND L. A. WEBB, *U. S. Naval Radiological Defense Laboratory.*—At low temperatures, trapped paramagnetic radicals are a prominent radiation product in organic compounds such as the alcohols. The electron paramagnetic resonance (EPR) hfs, resulting from the magnetic moment of the hydrogen nuclei, provides information regarding the identity and structure of these radicals. Previous measurements on methanol, ethanol, and propanol show a carbon-hydrogen bond has been ruptured in forming the radicals. In this study, molecules of *n*-propanol were tagged with deuterium to assist in determining which bond breaks preferentially. The following compounds were irradiated at 77°K with electrons or x rays from a 2-Mev Van de Graaff generator: I, $CH_3CH_2CD_2OH$; II, $CH_3CD_2CH_2OH$; III, $CD_3CH_2CH_2OH$; IV, $CH_3CH_2CH_2OH$. Their EPR hfs measured at 9.5 kMc and 77°K showed a coupling between the deuterium nuclei and the unpaired electron in compounds I and II. The 5-line hf spectra for III and IV were very similar and gave no indication of coupling to the deuterium. Additional evidence for the preferential removal of deuterium from the α and β carbon positions was obtained by mass spectrographic analysis of the gases liberated by irradiation of solid samples. Relative deuterium concentrations of I, 3.1; II, 1.5; and III, 1.0, were found. The measured EPR hfs will be compared to spectra constructed from Gaussian shaped absorption bands for the four compounds assuming a broken α hydrogen link.

DA11. Estimation of Heats of Formation of C-H Radicals.* M. COWPERTHWAITE AND S. H. BAUER, *Cornell University.*—During the pyrolysis of hydrocarbons above 2000°K in a shock tube, the system reaches a state of equilibrium, except with respect to the precipitation of solid carbon. The equilibrium composition may be computed. Preliminary estimates show that species such as C_3H, C_3H_2, C_4, C_4H, C_4H_2 (diacetylene), C_4H_3, C_4H_4 (butatriene and vinyl acetylene), C_5, C_5H, C_6, C_6H, etc. must be considered as participating in the complex of coupled equilibria. For each molecular type, one must estimate (a) the principal moments of inertia, the fundamental vibrational frequencies, and the electronic degeneracies necessary for calculating $(F_T^\circ - H_0^\circ)$, and (b) the standard heat of formation ΔH_{0f}°. We describe an empirical method for estimating the heats of formation. For presumed similar processes, known bond dissociation energies are compared with those not known. In each step, magnitudes are assigned for the isovalent dissociation, for changes in hybridization and for nonlocalized *p*-orbital interactions. The selected standard reactions involve the successive stripping of hydrogen atoms from C_2H_6 and C_3H_8. For example, the estimated ΔH° for the dissociation $C_3H_5 = C_3H_4 + H$ is 63 kcal/mole compared with 65 kcal based on experimental dissociation energies; two independent estimates of ΔH_{0f}° for butatriene are 61 and 64 kcal/mole; for C_4H_3, two paths lead to 100 kcal/mole.

* This work was supported by the Air Force to which grateful acknowledgment is made.

DA12. Comparison of Liquid and Gaseous State Absolute Infrared Intensities for CCl_4, $CHCl_3$, and $CHBr_3$. L. P. LINDSAY, S. MAEDA,* AND P. N. SCHATZ, *University of Virginia.*—For the molecules CCl_4, $CHCl_3$, and $CHBr_3$, measurements and calculations have been made which permit several comparisons of the absolute infrared intensity of a given band in the pure liquid (A_l) with the absolute intensity of the corresponding band of the same molecule in the gas (A_g). Preliminary results are as follows: $A_l/A_g = 1.2$ (CCl_4, 13 μ region); $= 1.0$ ($CHCl_3$, 13.25 μ band); $= 1.3$ ($CHCl_3$, 8.24 μ band). In the case of CCl_4, the intensity was measured in the vapor and compared with the liquid value previously reported by Kagarise.[1] For pure liquid $CHCl_3$, the intensities were calculated from Pittman's dispersion data[2] and compared with the gas values of Morcillo et al.[3] For $CHBr_3$, the corresponding liquid intensities were calculated in the same way, and vapor phase intensity measurements are in progress. The relation of the present results to the Polo-Wilson equation will be discussed.

* On leave of absence from the National Defense Academy, Yokosuka, Japan.
[1] R. E. Kagarise, J. Chem. Phys. 31, 1258 (1959).
[2] M. A. Pittman, J. Opt. Soc. Am. 29, 358 (1939).
[3] Morcillo, Herranz, and Fernandez Biarge, Spectrochim. Acta 10, 110 (1959).

DA13. Determination of the Vapor Pressure or of the Oscillator Strengths of Atomic Species by Absorption Spectroscopy.* GUIDO L. VIDALE, *General Electric Aerosciences Laboratory.*—A method has been developed for measuring the equilibrium pressure of atomic species, which is of special applicability for the study of the vapor pressure of refractory ceramics. A resonance line of known oscillator strength for the atomic species under examination is generated in a liquid nitrogen cooled, hollow cathode discharge tube, and its absorption by the hot equilibrium gas is used to determine its vapor density. The gas being studied is contained in a diffusion limited cell of constant temperature. Temperatures to 1850°C have been maintained in an oxidizing atmosphere and to 3000°C in a reducing atmosphere. The vapor density is calculated assuming that the line from the discharge tube is infinitely thin. Doppler broadening, pressure broadening, pressure shift, and hyperfine structure of the line are discussed quantitatively. Experimental results obtained for the oscillator strength of sodium atomic lines are given in order to indicate the accuracy of density determinations by this method. New values are reported for the oscillator strength of the Cu_{3247} and the Si_{2516} lines.

* This work was performed under the auspices of the U. S. Air Force, Ballistic Missile Division.

DA14. Hydromagnetic Stability of Rotating Spherical Shells with Distributed Heat Sources. I. WILLIAM GINSBERG AND A. F. STEVENSON, *Wayne State University.**—The stability of a rotating spherical shell of liquid, placed in a uniform magnetic field and subject to its own gravitation, has been investigated. The liquid is assumed to be conducting and to contain distributed heat sources, the boundary being rigid. A variational method similar to that suggested by Chandrasekhar[1] has been employed to determine the Rayleigh number as a function of the relevant parameters.

* This paper placed on Monday afternoon to avoid simultaneity with another paper by one of the authors.
[1] S. Chandrasekhar, Phil. Mag. 2, 1282 (1957).

MONDAY AFTERNOON AT 2:15

Auditorium, Institute of Arts

(W. C. DASH presiding)

DSSP Symposium on Dislocations

E1. Origins and Motions of Dislocations in Crystals. J. J. GILMAN, *General Electric Research Laboratory.* (30 min.)

E2. Observations on Dislocations in Metals with the Electron Microscope. H. G. F. WILSDORF, *Franklin Institute.* (30 min.)

E3. Plastic Deformation of Dislocation-Free Silicon and Germanium. J. R. PATEL, *Raytheon Research Division.* (30 min.)

E4. Dislocation Contributions to the Elastic Constants and Damping at Megacycle Frequencies. G. ALERS, *Ford Motor Company.* (30 min.)

MONDAY AFTERNOON AT 2:15

Auditorium, Engineering Society

(W. KAENZIG presiding)

Electron-Spin Resonance

F1. Hyperfine Structure of the $(Cr^{53})^{+++}$ Ion in Ruby by Double Resonance.* R. W. TERHUNE, C. KIKUCHI, J. LAMBE,† AND J. BAKER, *The University of Michigan, Willow Run Laboratories.*—The hyperfine spectrum of the trivalent Cr^{53} ions was obtained by observing the change in the electron spin resonance absorption under saturation conditions as the frequency of an rf oscillator connected to a coil around the ruby was scanned. Four triplets were observed centered near 25 and 75 Mc with the magnetic field along the crystal c axis. Preliminary analysis indicates that $A=48.5$ Mc/sec in good agreement with the 51 Mc/sec value of Manenkov and Prokhorov.[1] The details of the spectra at 0° and 90° will be presented and compared to theory.

* Supported by Project MICHIGAN (administered by the U. S. Army Signal Corps), and by the Air Force Office of Scientific Research.

† Now with the Scientific Laboratory, Ford Motor Company, Dearborn, Michigan.

[1] A. A. Manenkov and A. M. Prokhorov, Zh. e'ksper. Teor. Fiz. **31**, No. 2(8), 346–347 (1956).

F2. Exchange Interactions in the Paramagnetic Resonance Spectrum of Ruby. M. J. WEBER, L. RIMAI, H. STATZ, AND G. A. DEMARS, *Raytheon Company,* AND G. F. KOSTER, *MIT.*—The paramagnetic resonance spectrum of ruby crystals with chromium concentrations ranging up to 1% have been investigated at 16 kMc. In addition to the spectrum of isolated Cr^{3+} ions, a very complex spectrum of weak lines is observed. The intensities of these additional lines and their dependence on chromium concentration suggest that they arise from coupled Cr^{3+} ions. Nearest-neighbor Cr-Cr pairs in Al_2O_3 may interact by a superexchange mechanism via the intervening oxygen atoms. If a pair of chromium ions is coupled by an isotropic exchange interaction of the form $J\mathbf{S}_1\cdot\mathbf{S}_2$, states of resultant spin $S=3$, 2, 1, 0 are formed with energies of $6J$, $3J$, J, and 0, respectively. The spectrum has been studied in the temperature range from 1.6° to 300°K. Measurements of the temperature dependences of several lines have been compared with the temperature dependences predicted for transitions within the various S multiplets, assuming antiferromagnetic coupling. A value of $J\sim250$ cm^{-1} is obtained. The presence of other ferro- and anti-ferromagnetically coupled pairs will be discussed.

F3. Spectrum of Exchange Coupled Cr^{3+} Pairs in Ruby. H. STATZ, L. RIMAI, M. J. WEBER, AND G. A. DEMARS, *Raytheon Company,* AND G. F. KOSTER, *MIT.*—The paramagnetic resonance spectrum of ruby with relatively large chromium concentrations (~1%) has been carefully examined. To explain the origin and frequency of numerous weak spectral lines, a Hamiltonian has been used which includes (1) an isotropic exchange term of the form $J\mathbf{S}_1\cdot\mathbf{S}_2$, (2) the sum of the spin Hamiltonians for spins 1 and 2, and (3) dipolar, pseudo-dipolar, and higher order anisotropy exchange terms. (1) is considered to be very much larger than the other terms in the Hamiltonian. The theory is developed for spin pairs whose axis is parallel to the c axis of the ruby crystal. This corresponds to pairs formed by Cr ions occupying nearest-neighbor cation sites in the Al_2O_3 lattice. Detailed measurements have been made of those lines which have a temperature dependence indicative of large J interactions and which exhibit a symmetric rotation pattern with respect to the c axis. Agreement between the observed spectrum and the spectrum predicted by the above Hamiltonian is obtained by using anisotropic exchange terms of the order of 0.5 cm^{-1}. Further evidence to support the spectral assignment is obtained from the angular dependence of the lines.

F4. Spin-Phonon Interaction in Ruby. E. B. TUCKER, *General Electric Research Laboratory.*—By use of techniques previously described,[1] the interaction of 9.2-kMc phonons with the Cr^{+++} spins in a piece of ruby bonded to a quartz rod has been observed. The bandwidth for the interaction is somewhat smaller than the microwave line width. By determining the law according to which the ultrasonic phonons saturate the spin resonance it is possible to extract the relative matrix elements for the spin-phonon interaction from the experimental data. This data consists of the variation of the spin-phonon interaction with θ (the angle between the dc magnetic field and the axis of symmetry in ruby) for the various lines in the spin resonance spectrum or ruby. The experimental results and comparisons with some of the theoretically predicted transition probabilities will be presented.

[1] E. H. Jacobsen, N. S. Shiren, and E. B. Tucker, Phys. Rev. Letters **3**, 81 (1959).

F5. Optical and Paramagnetic Resonance Spectra of Cr^{+++} in Ga_2O_3. M. PETER AND A. L. SCHAWLOW, *Bell Telephone Laboratories.*—Single crystals of β-Ga_2O_3 with Cr^{+++} doping were grown by J. P. Remeika. The optical transitions $^2E \rightarrow {}^4A_2$ of Cr^{+++} have been observed in fluorescence. At 4.2°K the one remaining emission line is sharp enough that the ground state splitting is resolved and the splitting is found to be 35.4±0.5 kMc/sec. The shorter component is twice the longer. The intensity ratio of the components suggests that both the upper and lower levels are inverted relative to those of ruby. The ground state splitting was also investigated with millimeter wave paramagnetic resonance and is described by the usual second-order spin hamiltonian ($S=\frac{3}{2}$) and the parameters: $D=+16.3$; $E=4.0$; $g_z=1.95$; $g_x=g_y=1.96$. This gives an independently measured natural splitting 35.4 kMc/sec and confirms the sign of D. The y axis falls into [010], and x almost coincides with [100] (for $a>c$). Correlation with S. Geller's recent structure determination (to be published) and with the corresponding ruby spectra will be discussed.

F6. Paramagnetic Resonance of Nickel in Al_2O_3.* S. A. MARSHALL, *Armour Research Foundation.*—A magnetic resonance absorption spectrum has been observed, at room temperature, in Al_2O_3 single crystals doped with nickel. The spectrum is interpreted as being due to nickel in the divalent state. From the symmetry of the magnetic spectrum it is suggested that the divalent nickel ions are located at sites normally occupied by aluminum ions. The parameters to the spin Hamiltonian are observed to be temperature dependent with $g_{11}=2.196$, $g_{\perp}=2.187$, $D=1.375$ cm^{-1} at room temperature and $g=2.156$, $D=1.312$ cm^{-1} at 77°K. Total nickel concentration, determined by neutrons activation analysis, is given by 6.0×10^{17} atoms/cc of Al_2O_3. The absorption intensity of the divalent nickel magnetic resonance indicates a concentration of 1.5×10^{17} ions/cc of Al_2O_3.

* Supported by Cambridge Air Force Research Center.

F7. (Abstract withdrawn.)

F8. Spin Resonance of Mn^{++} in CdTe. J. LAMBE, *Ford Motor Scientific Laboratory,* AND C. KIKUCHI, *University of Michigan.** Following the suggestion by Dorain,[1] single crystals of CdTe containing 0.01% Mn^{++} were investigated in an X band ESR spectrometer at 300°, 78°, and 4.2°K. At room temperature, only the 6 broad Mn-55 hfs lines are observed. At 78°K, the lines narrow, the fine structure components are resolved and at 4.2°K, the principal hfs lines split into a number of superhyperfine structure components due to Cd nuclei. The cubic zero field splitting, $3a$, for CdTe is 0.0084 cm^{-1}, compared to 0.00233 cm^{-1} for ZnS, despite the fact that the anion-cation distances in CdTe and ZnS are 2.78 and 2.36 A, respectively. The g value shift is positive. The superhyperfine component spacing is 1.4 gauss, equal to that in CdS. The broadening of the lines at 300°K in CdTe is due to spin lattice interaction indicating a T_1 of about 10^{-8} sec, which is much shorter than is observed in CdS and ZnS. In CdS, broadening effects are observed only when a fairly high number of conduction electrons are present. This effect is then due to an interaction between conduction electrons and Mn^{++}.

* Supported in part by Air Force Office of Scientific Research.
[1] P. B. Dorain, Phys. Rev. 112, 1058 (1958).

F9. (Abstract withdrawn.)

F10. Forbidden Hyperfine Transitions in Electron Spin Resonance. G. W. LUDWIG AND H. H. WOODBURY, *General Electric Research Laboratory.*—Consider a crystal containing unpaired electrons and nuclei of nonzero spin. If it is not possible to choose an axis of quantization such that m is a good quantum number for a particular nucleus, "forbidden" ($\Delta M=\pm1$, $\Delta m\neq0$) transitions become allowed. In particular, the m states of the nucleus will be mixed if there are several interactions (represented by terms of comparable size in the spin Hamiltonian) which tend to align the nucleus along different axes in space. Bleaney[1] has discussed the case where the nuclear quadrupolar interaction PI_z^2 competes with the direct interaction $-g_I\beta_N H\cdot I$ of the nucleus with the external field. It is also true, however, that forbidden hyperfine transitions will occur if the electronic DS_z^2 term competes with the $g\beta S\cdot H$ term. The DS_z^2 term mixes states of different M; states of different m are then mixed by the term $\frac{1}{2}A(S_-I_+ + S_+I_-)$ in the Hamiltonian. Forbidden hyperfine transitions of this type have been observed in the spectra of several impurity pairs in silicon, $(MnB)^+$, $(MnZn)^0$, etc. Another case of interest is $DS_z^2 \gg g\beta S\cdot H$, where forbidden transitions occur when $AS\cdot I$ and $-g_I\beta_N H\cdot I$ are comparable.

[1] B. Bleaney, Phil. Mag. 42, 441 (1951).

F11. Spin Resonance of Ni, Pd, and Pt in Silicon. H. H. WOODBURY AND G. W. LUDWIG, *General Electric Research Laboratory.*—Spin resonance of some transition metal impurities (V^{++}, Cr^{+}, Mn^{-}, Mn^{++}, and Fe^{0}) in Si has been reported.[1] Ni, Pd, and Pt impurity atoms in Si have also been found to be electrically active and, if properly compensated, each will show resonant absorption. Unlike the impurities discussed in reference (1), the resonance patterns of the Ni-group impurities must be described by an anisotropic g-tensor because of spontaneous distortions from the normal symmetrical lattice positions. Pd and Pt appear to be substitutional acceptors while Ni is an interstitial donor. The spectrum of Pd^- in Si is similar to that of Ni^- in Ge,[2] with $g_1=1.919$, $g_2=2.059$, and $g_3=1.972$ in the notation of reference (2). Two different spectra due to Pt^- have been seen; the one of present interest shows considerable anisotropy, the principle g-values being 1.427, 2.079, and 1.387. Ni^+ in Si is interesting in that only below 4°K does the distortion become fixed in the crystal; above this temperature a single isotropic line is observed because of motional averaging.

[1] H. H. Woodbury and G. W. Ludwig, Phys. Rev. 116 (Dec. 15, 1959), (to be published).
[2] G. W. Ludwig and H. H. Woodbury, Phys. Rev. 113, 1014 (1959).

F12. Anisotropy of the Spin-Lattice Relaxation Time of Donor Electrons in Ge and Si.* HIROSHI HASEGAWA, *Carnegie Institute of Technology.*—We have calculated the spin-lattice relaxation time of donors in Ge and Si due to one-phonon processes.[1] This relaxation time T_s depends on the orientation of the static magnetic field with respect to the crystal axes. When the field lies in a {110} plane, the angular dependence of $1/T_s$ is expressed by the factors $f_{Ge}(\theta)=\cos^4\theta+\frac{1}{3}\sin^4\theta$, $f_{Si}(\theta)=\frac{1}{4}\sin^2\theta(1+3\cos^2\theta)$, for donors in Ge and Si, respectively, where θ is the angle between the field and a ⟨100⟩ axis. In the case of Si, this prediction has been compared with the preliminary results of an experiment by G. Feher[2] on the anisotropy of T_s for phosphorus donors in Si, and qualitative agreement has been obtained. There is however an indication that some other significant relaxation mechanism is also present. Further correlations between theory and experimental results will be discussed.

* Supported by the Office of Naval Research.
[1] See also L. M. Roth, Bull. Am. Phys. Soc. Ser. II, 5, 60 (1960).
[2] G. Feher (private communication).

F13. Electron-Spin Resonance of Irradiated Ferroelectrics. GERALD BURNS, *IBM Research Laboratory.*—Chynoweth has shown the ferroelectric hysteresis loops in tri-glycine sulfate (TGS) are altered when the crystal is irradiated with x-rays. Here the results of electron resonance measurements on the ferroelectrics, TGS, Rochelle Salt (RS), $LiN_2H_5SO_4$, $C(NH_2)_2Al(SO_4)_2\cdot 12H_2O$(GASH), and $LiH_3(SeO_3)_2$ are reported. X-rays from a molybdenum tube run at 35 Kev and 10 ma were used. The effect on the loops is not the same in all cases: the $LiN_2H_5SO_4$ loop decays to a straight line in a matter of minutes; in $LiH_3(SeO_3)_2$ the coercive field increases; the effect in GASH is similar to TGS. There are some time effects in the resonances. The figures quoted refer to measurements taken ≈hours after irradiation. In TGS when the c axis is parallel to H_0 the resonance looks principally like a triplet with an over-all splitting of 28 gauss. However, it breaks up into a number of lines at other orientations. A polycrystalline sample gives a broad line with no resolution. RS has essentially five lines fairly independent of orientation. With the c axis parallel to H_0 the separation between the extreme lines is 51 gauss; the next pair 24 gauss. The central line has a slightly smaller g. $LiN_2H_5SO_4$ powder has nine lines, the separation between each is 13 gauss. A single crystal with the c axis parallel to H_0 has at least fifteen lines.

F14. Paramagnetic Resonance Studies of Optical Effects in SrS: Eu, Sm. REUBEN S. TITLE, *I. B. M. Research Laboratory, Poughkeepsie.*—The phosphor SrS: Eu, Sm is known to store energy when irradiated with ultraviolet or blue light. The storage of energy involves the ionization of europium normally present as Eu^{2+} to Eu^{3+} with the liberated electron being trapped by the samarium. The storage involves a change in the valency of Eu and therefore manifests itself as a decrease in the magnitude of the EPR spectrum of Eu^{2+}. This has been used to plot the dependence of storage on the wavelength of exciting light.[1] Exhaustion of energy from the sample is achieved by irradiating it with a wavelength capable of ionizing samarium sites containing trapped electrons. This releases the electron which can be captured by Eu^{3+} reconverting to Eu^{2+}. In this case of exhausting the sample the Eu^{2+} EPR spectrum therefore increases. A plot of exhaustion efficiency against the wavelength of exhausting light was carried out. Three peaks were found at 950 mμ, 590 mμ, and 375 mμ. The variation of storage efficiency in this phosphor with varying concentrations of the activators Eu and Sm was also determined.

[1] R. S. Title, Phys. Rev. Letters 3, 273 (1959).

MONDAY AFTERNOON AT 2:15

WSU McGregor Memorial

Conference Center Room L

(E. N. ADAMS presiding)

Invited Paper

FA1. Experimental Investigation of the Structure of Shallow Impurity States in Germanium. H. FRITZSCHE, *University of Chicago.* (30 min.)

Transport Properties: Silicon and Germanium, I

FA2. Incipient Impurity Conduction in Silicon. M. POLLAK AND T. H. GEBALLE, *Bell Telephone Laboratories.*—The complex conductivity of n-Si has been measured in the concentration range where "hopping" of electrons between localized donor states is possible. The measurements were performed as a function of frequency and temperature in samples of various impurity concentration and degree of compensation. The temperature range was 1–20°K; the frequency range 10^2–10^5 cps. The majority impurity was phosphorus. It was present in a concentration of the order of 10^{16} atoms per cc. so that while incipient impurity conduction took place, dc losses were small. The minority impurity varied from residual contamination to about 10^{15} boron atoms per cc. For comparison, a very pure sample was also measured. In the pure sample the real part of the conductivity was extremely small ($<10^{-13}$ ohm^{-1} cm^{-1} at 4.2°K) and the dielectric constant practically independent of frequency and temperature. In contrast, in the doped samples the dependence of both on temperature and frequency was pronounced. The rather strong frequency dependence suggests that "hopping" occurs predominantly in localized parts of the crystal, presumably in the neighborhood of minority impurities. This view is supported by the significant increase of conductivity with the degree of compensation. At low temperatures the dielectric constant approached a value independent of frequency and the losses became small. This is in agreement with a model in which the hopping is phonon induced.

FA3. Impurity Conduction at Low Concentrations.* ALLEN MILLER† AND ELIHU ABRAHAMS, *Rutgers University.*—The conductivity and Hall effect of n-type semiconductors has been investigated at low temperatures T and low impurity

concentrations N_d. The model is that of phonon-induced electron transfer of a localized state at a donor site to a nearby vacant site. To first order in the electric field, the solution of the steady state and current equations is shown to be equivalent to the solution of a resistance network. Each pair of sites in the network is connected by an element whose resistance is inversely proportional to the transfer rate between the sites. The T dependence of the resistivity is given by $\rho \sim \exp(\epsilon_3/kT)$ where $\epsilon_3=(e^2/K_0)(r_d^{-1}-1.35r_a^{-1})$ at low compensations $K=N_a/N_d$. The lengths r_d and r_a^{-1} are defined by $N_{d,a}^{-1}=4\pi r_{d,a}^3/3$. At higher K, ϵ_3 and ρ attain a minimum between $K=0.45$ and $K=0.55$. It is found that in the absence of spin-orbit coupling, the model gives a vanishing Hall current which is consistent with experimental results.

* Supported in part by Office of Naval Research.
† Now at University of Illinois.

FA4. Electron-Electron Scattering in *n-p* Tunneling. EVAN O. KANE, *Hughes Products.*—The *I-V* characteristics of *p-n* junction diodes show large thermionic currents at forward biases where the energy bands have been "uncrossed." This "excess" current implies the existence of significant energy loss mechanisms in or near the junction. A simple model of such a mechanism postulates the perfect crystal band structure modified only by "tunneling" wave functions extending into the gap. Energy is absorbed either by phonons, photons, or another electron. The first two mechanisms are presumably too small to be important. We have calculated the electron mechanism and find that it also is incapable of explaining the observed current. The electron-electron scattering mechanism was calculated assuming a constant junction field and parabolic energy bands. In the junction region "tunneling" functions

$$q_n(k)=\exp(i/F)\int_0^{k_x}\{E-E_n(k')\}dk'x$$

were used where F is the constant force on the electron and E is the energy. The functions are written in Bloch space. Two electrons tunnel in from the n side. One electron drops into a tunneling hole and gives up its excess energy to the other electron. The semiclassical method of stationary phase was employed. This method is a generalization of the familiar WKB method.

FA5. Determination of Forward and Reverse Tunneling Currents in Esaki Diodes by Shot Noise Measurements. C. A. LEE AND H. C. MONTGOMERY, *Bell Telephone Laboratories.*—A method is presented whereby one may determine separately the forward and reverse tunneling currents in an Esaki diode of germanium. At a frequency sufficiently high to observe wholly a white noise spectrum, the tunneling currents produce full shot noise corresponding to the sum of the currents, while the dc bias current provides a measure of the difference of the two tunneling currents. The magnitude of these two tunnel currents at zero bias is a measure of the occupation of energy levels very near the Fermi level and it is clear that a small forward bias of $\sim 2\ kT$ should reduce the reverse tunnel current almost to zero. Measurements are presented as a function of temperature and bias which support such an interpretation of tunneling processes in Esaki diodes.

FA6. Temperature Dependence of Current in Esaki Diodes. R. A. LOGAN AND A. G. CHYNOWETH, *Bell Telephone Laboratories.*—As the applied forward bias is increased in an Esaki diode, one observes first, a current maximum, I_p, then a current minimum, I_v, and finally the ordinary diode forward current. I_v is well in excess of the ordinary diode current as extrapolated from the portion of the curve at high forward bias. I_p and I_v have been measured over the temperature range 10°–350°K in Si, Ge and InSb diodes. The shape of the I_p vs T curves shows structure in the case of Si, but not for Ge or InSb. This is in agreement with similar measurements[1] of the reverse current flow where the current was shown to be due primarily to internal field emission across the indirect energy gap, E_I, in Si, and the direct gap, E_D, in Ge and InSb. The temperature variation of I_p is determined by that of E_D for Ge and InSb; but for Si, in addition to the temperature variation of E_I, there is a contribution due to that of the phonon density, thus giving rise to the observed structure. No such phonon effects have been observed in I_v, even in the case of Si. This fact restricts the models which may be proposed for this excess current, and in particular, it appears to rule out one hypothesis for I_v, namely, indirect transitions with photon emission.

[1] A. G. Chynoweth *et al.*, Phys. Rev. (to be published).

FA7. On the Nature of the Maximum and Minimum Currents in Germanium Tunnel Diodes. T. A. LONGO, *Sylvania Electric Products, Inc.*—The quantum mechanical tunneling effect has been studied in a wide variety of germanium narrow *p-n* junction systems. Such junctions have been fabricated with indium alloying material containing varying amounts of gallium doping and with degenerate germanium doped with arsenic, phosphorus and combinations of these. The highest current ratios have been observed when using arsenic doped germanium; however, the highest current densities thus far attained (4000 amp/cm²) have been observed when using the phosphorus plus arsenic doping. Negative and positive temperature dependences of the current maximum have been both observed. These would appear to reflect independently: (1) the temperature effect on the energy distribution of free carriers about the Fermi level in the carrier bands; (2) the temperature effect due to the sensitivity of the tunneling probability to the temperature dependent E_g. At liquid nitrogen temperature a structure is observed in the minimum current region of the current voltage characteristics obtained from junctions fabricated with germanium doped with phosphorus. This suggests a mechanism of tunneling from carrier band to carrier band via deep lying intermediate states. This hypothesis is supported with the results of irradiation with 7-Mev electrons. It is observed that the predominant effect of irradiation is the increase of current minimum.

FA8. Efficiency of Solar Energy Converters.* HANS J. QUEISSER AND WILLIAM SHOCKLEY, *Shockley Transistor Corporation.*—Calculations for the theoretical efficiency of solar cells generally use empirical information on the current-voltage characteristics of *p-n* junctions.[1] In order to find an upper theoretical limit, an ultimate efficiency has been calculated for the ideal case in which there is only the radiative recombination required by the principle of detailed balance between created hole-electron pairs and that the cell is entirely surrounded by a blackbody of sun temperature. The fraction of this ultimate efficiency is calculated for a real solar energy converter, where nonradiative recombination processes are more frequent than radiative ones by a factor ρ, estimated from respective lifetimes. The limited solid angle subtended by the sun and reflectivity are taken into account. Maximum power output efficiency at matched loads has been obtained with band gap, temperature, and ρ as parameters. The results are compared to experimental yields.

* Research supported by Wright Air Development Center.
[1] J. J. Loferski, J. Appl. Phys. **27**, 777 (1956).

FA9. Removal of Metal Precipitates and Hardening of Soft Silicon *P-N* Junctions by "Gettering."* ADOLF GOETZBERGER, *Shockley Transistor Corporation* (introduced by W. Shockley).—It has been shown[1] that certain surface treatments at high temperature will improve lifetime in silicon. Further evidence that such action involves gettering of metallic impurities by the surface phase is furnished by the

removal by similar gettering of "softness" in reverse *V-I* characteristics. This softness is deliberately produced by processes calculated to produce metallic precipitates in the space charge layer.[2] The experimental procedure involved the following steps: (a) Production of soft junctions by either diffusion of impurities for a long period of time at very high temperature or by indiffusion of softness causing elements into junctions, (b) Gettering treatment: Metallic coatings and certain glassy oxide layers were investigated. Results indicate that layers of nickel and zinc have a certain gettering effect. Glassy layers containing certain oxides, especially those of boron and phosphorus, were found to have the greatest gettering effect.

* Supported in part by Air Force Cambridge Research Center Contract.
[1] G. Bemski, Phys. Rev. **103**, 567 (1956).
[2] A. Goetzberger and W. Shockley, *Structure and Properties of Thin Films* (John Wiley and Sons, Inc., New York, 1959), pp. 298–301; and Bull. Am. Phys. Soc. Ser. II, **4**, 409 (1959).

FA10. Statistical Fluctuations of Donors and Acceptors in *p-n* Junctions.* WILLIAM SHOCKLEY, *Shockley Transistor Corporation.*—Reverse biased *p-n* junctions usually have localized regions of low avalanche breakdown voltage due to dislocations and other inhomogeneities but even a structurally perfect crystal will have statistical inhomogeneities if the donors and acceptors are distributed at random. For example, in an abrupt $(p+)n$ junction with breakdown voltage V_B, field E_B, space-charge width W, donor concentration N_D, and dielectric constant K, the number of donor ions cooperatively producing the avalanche field in any small region is approximately $m=N_DW^3=4KV_B^2/qE_B\cong 50V_B^2$ for silicon. For a 10-v junction $m=5000$ and the rms deviation is 70 or 1.4% leading to a $\pm 1.4\%$ mean spread of breakdown voltage; there are about 6×10^6 mm^{-2} such regions so that a few relatively low breakdown spots are probable. In abrupt Esaki tunnel diode junctions, the number of cooperating ions in W^3 is $(2KV/q)^{\frac{1}{2}}/N_D^{\frac{1}{2}}\cong 100$ for $N_D>10^{19}$ cm^{-3}. Significant fluctuations in lower band edge may result just outside the space charge layer and contribute to the current and voltage values at the current minimum.

* Supported in part by U. S. Air Force Cambridge Research Center.

MONDAY AFTERNOON AT 2:15

Auditorium, Rackham Memorial

(FRANK HERMAN presiding)

Invited Paper

G1. Band Theory of Alkali Metals. F. HAM, *General Electric Research Laboratory.* (30 min.)

Energy-Band Theory; Magnetic Susceptibility

G2. The Application of Dispersion Relations to Bloch Functions. PETER E. KAUS AND W. K. R. WATSON, *University of Southern California,* AND RICHARD E. NORTON, *California Institute of Technology.*—On the assumption of the causality of the Green's function which generates the Bloch functions $\Psi(k,x)$ in terms of the free space wave functions it can be shown that the Floquet factor $e^{ik(E)a}$ is analytic in the upper half energy plane. By the direct application of Cauchy's theorem to this quantity, four dispersion relations have been derived which relate the wave number k at one energy to the wave number at all others. In particular, the imaginary part of the wave number k_i in a forbidden gap may be equated to an integral of a function of the real part of the wave number k_r over allowed energies. By transferring the integrals from E space to k space these relations take on a more physically appealing form and it is hoped that they can be used explicitly for calculations involving tunneling processes, impurity wave functions, etc. Moreover, these dispersion relations allow certain theorems regarding the location of the branch points to be established.

G3. The Crystalline—WKB Approximation. G. A. PETERSON,* *Cornell University.*—Block WKB functions are taken as approximations to the linearly independent solutions for a conduction band electron in a slowly varying external field. The phase $S_0(\mathbf{r})$ is determined by the crystalline-eikonal equation $E(\nabla S_0)=E-H_1(\mathbf{r})$. Near zone turning points the analysis fails since the effective mass particle sees the Brillouin zone edge as a classical turning point. Connecting relations are developed in one dimension which match the correct linear combination of propagating waves across the zone boundary onto the forbidden band functions. A phase integral condition fixes the allowed energies. Applications are made to the one-dimensional impurity well, the uniform electric field and the homogeneous magnetic field. This approximation can be understood by introducing an eikonal in the Wannier-Slater equation and segregating powers of $\hbar$ as $\hbar\to 0$.

* Supported in part by the Office of Naval Research.

G4. Electronic Band Structure of Aluminum. B. SEGALL, *General Electric Research Laboratory.*—A detailed calculations of the energy bands of Al was carried out for the symmetry points and lines of the Brillouin zone by the Kohn-Rostoker-Korringa method.[1] The potential employed was essentially the one used by Heine[2] except for a correction of an error[3] and for a small difference arising from the requirement that the potential be constant in the corners of the atomic polyhedron. The method exhibited very rapid convergence at all $\mathbf{k}$ investigated. Except near the zone boundaries, where there are small gaps, the bands are free-electron-like throughout the zone. The results do not differ significantly from the values calculated by Heine at the symmetry points aside from the point K in the third zone. Here our value is several volts lower than his, a discrepancy also noted by Harrison.[4] A comparison of the present results with the work of Harrison[4] who used a pseudo-potential interpolation method will also be presented.

[1] W. Kohn and N. Rostoker, Phys. Rev. **94**, 1111 (1954); J. Korringa, Physica **13**, 392 (1947).
[2] V. Heine, Proc. Roy. Soc. (London) **A240**, 361 (1957).
[3] R. E. Behringer, J. Phys. Chem. Solids **5**, 145 (1958).
[4] W. Harrison, Phys. Rev. (to be published).

G5. The Electronic Properties of Aluminum. WALTER A. HARRISON, *General Electric Research Laboratory.*—Calculations of the band energies at symmetry points in aluminum by Heine[1] have been extended into the zone using a pseudo-

potential interpolation scheme in order to obtain constant-energy curves in the neighborhood of the Fermi surface. Interesting cross sections of the Fermi surface have been calculated in detail and will be displayed. The de Haas-van Alphen periods, cyclotron-resonance masses, orientation-dependence of the anomalous skin effect, and low temperature specific heat have been calculated from these surfaces and will be compared with experiment. It is found that, though the geometry of the surfaces seems to be very well given by the calculation, there is a discrepancy of a factor of two in the measured and calculated effective masses. A "single-orthogonalized-wave approximation" is compared with the more exact treatment and found to be in semiquantitative agreement with respect to parameters which enter the electronic properties.

[1] V. Heine, Proc. Roy. Soc. (London) **A240**, 361 (1957).

G6. Energy Band Calculations for Alkalis with the Composite Wave Representation. H. SCHLOSSER, *Carnegie Institute of Technology*, and P. M. MARCUS, *IBM Research*.—A new technique for the calculation of electronic energy bands in solids has been developed and tested on Li and Na, yielding results of high accuracy even for arbitrary points in the Brillouin zone. The technique utilizes a composite wave function expanded in symmetrized plane waves in the outer part of the cellular polyhedron and matched on the inscribed sphere to a spherical wave expansion inside the sphere. (Generally the derivative of the wave function is discontinuous on the sphere.) A variational principle for wave functions with discontinuities on surfaces in the cell is used to determine the best eigenvalue for a given number of plane waves and gives a generalized secular equation in which the unknown eigenenergy appears in all matrix elements. An IBM-704 program for the automatic high speed generation of matrix elements and solution of the resulting secular equation has been written and applied to 25 points in the Brillouin zone of Li and 15 points in Na, including a number of points without symmetry. Agreement to four significant figures is found with Kohn and Rostoker[1] for Li, and close agreement with Ham[1] for Li and Na.

[1] W. Kohn and N. Rostoker, Phys. Rev. **94**, 1111 (1954); Frank Ham (private communication).

G7. Cubic Field Splitting of D Levels in Metals. JOSEPH CALLAWAY, *University of Miami* AND D. M. EDWARDS, *University of London*.—The crystal field splitting of d electron states in cubic metals is important in studies of the electronic structure of the transition metals. We have calculated this splitting for a potential produced by a lattice of positive point charges, Ze, (lattice parameter a). The calculation was done to first order in the cubic field. The triply degenerate d state is lowered with respect to the doubly degenerate state in both body centered and face centered cubic lattices. For hydrogenic radial d functions proportional to $r^2e^{-(\frac{1}{2})\kappa r}$ the cubic field splitting is proportional to $(Z/a)(\kappa a)^{-4}$. The constant of proportionality depends only on the type of lattice. For sufficiently large κa, the crystal field splitting is larger than the overlap splitting which decreases exponentially with κa. Analytic atomic wave functions were used to estimate the crystal field splitting in iron at the observed lattice spacing. The resulting splitting, $-0.1\ Z$ ev is much smaller than the overlap effect. These results do not support models in which the d band is split into subbands based on functions of t_{2g} and e_g symmetries.

G8. Preliminary Calculations on the Band Structure of CdS. D. A. COHEN* AND J. R. REITZ, *Case Institute of Technology*.—The electronic energy bands of cadmium sulfide are calculated using the "empirical potential" approach of Phillips and Kleinman[1] for $\mathbf{k}=0$ in the Brillouin zone. An approximate lattice potential is constructed from a superposition of atomic potentials. The atomic potentials are based on atomic wave functions formed from orthogonal linear combinations of Slater nodeless functions. A general expression is given for the matrix elements of the potential for symmetrized linear combinations of plane waves. The present study is intended more as a feasability study of the method for crystals of the Wurtzite structure rather than to obtain quantitatively accurate results. Preliminary results will be given.

* First Lieutenant, U. S. Air Force.
[1] J. G. Phillips and L. Kleinman, Phys. Rev. 116, 287 (1959).

G9. Magnetic Susceptibility of $p-$Ge. R. BOWERS, *Westinghouse Research Laboratories*.—The magnetic susceptibility of p-type Ge has been measured between 300°K and 1.3°K for carrier densities ranging from 5×10^{17} to 5×10^{20} cm^{-3}. The change in susceptibility with temperature is small for all carrier densities studied (less than 11% change between 300°K and 1.3°K). The carrier susceptibility in the low temperature degenerate limit has been derived from the data[1] in order to examine its variation as the Fermi level is lowered in the valence band. The Fermi level at absolute zero of the most highly doped specimen is 0.3 ev below the valence band maximum. The observed dependence of carrier susceptibility on carrier density can be explained in terms of the departure of $J=\frac{3}{2}$ bands from parabolic form at low carrier densities and also the population of the "split-off" band ($J=\frac{1}{2}$) at the higher carrier densities. The results appear to be in qualitative agreement with current models[2] of the valence band structure of Ge.

[1] R. Bowers, Phys. Rev. **108**, 683 (1957).
[2] E. O. Kane, J. Phys. Chem. Solids **1**, 83 (1956).

G10. Orbital Magnetic Susceptibility of Bloch Electrons. L. LIU AND MORREL H. COHEN, *University of Chicago*.—A complete expression for the magnetic susceptibility of Bloch electrons has been calculated by using the crystal momentum representation (CMR). Since this representation gives a clear distinction between the free-electron-like and atomic-like aspects of electronic motion, it serves to help us to group our final result into different terms according to their physical origin. It is found that in addition to the Landau-Peierls susceptibility, there are modified atomic diamagnetism, modified Van Vleck second-order paramagnetism, susceptibility from unquenched orbital angular momentum, and susceptibility from mixed atomic-like and free-electron-like motion. The result can be simplified if we assume that the crystal possesses inversion symmetry. For this case, the result can readily be expressed in terms of Bloch functions as well as CMR matrix elements. Since the calculation is lengthy, a critical test of the result is desirable. Such a check is provided by an arbitrary phase transformation of the Bloch functions, to which our results prove invariant. Comparison with other recent work[1,2] has also been carried out.

[1] J. E. Hebborn and E. H. Sondheimer, Phys. Rev. Letters **2**, 150 (1959).
[2] A. D. Brailsford (private communication).

G11. Steady Magnetic Susceptibility. E. I. BLOUNT, *Westinghouse Research Laboratories*.—The steady magnetic susceptibility of a crystal has been calculated, including spin-orbit effects, without any assumptions as to symmetry and neglecting electron-electron interactions. The procedure was to remove all first-order interband matrix elements of the Hamiltonian before evaluating the free energy. The resulting calculations are quite simple and straightforward and the terms can be given physical meanings. Familiar terms are the Landau-Peierls and atomic diamagnetism, the Van Vleck paramagnetism and a modified Pauli paramagnetism. The modification consists of an "effective g-factor" which reduces to 2 in the case of inversion symmetry and no spin-orbit coupling. An additional term is found which also reduces to

zero in this case. For Bi, on the other hand, these terms are very large. The Pauli term is actually larger than the Landau-Peierls diamagnetism. Thus the large diamagnetism of Bi is due to either the atomic diamagnetism or the 2nd new term. In any case it depends on features of the band structure which have not yet been explored experimentally. Large values for these terms are not unlikely for Bi on the basis of its known structure.

MONDAY AFTERNOON AT 2:15

WSU Community Arts Auditorium

(R. T. WEBBER presiding)

Superconductivity and Thermal Properties

GA1. Surface Impedance of a Superconductor in a Magnetic Field; Theory.* G. DRESSELHAUS AND M. S. DRESSELHAUS, *Cornell University.*—A two-fluid model has been applied to calculate the quadratic term, i.e., H^2 term, in the variation of surface impedance with magnetic field. The superconducting electrons are assumed to satisfy the London equations while the normal electrons follow a nonlocal relation. Consideration is given to the two limiting cases of the classical and the extreme anomalous limit of the skin effect. Results are obtained in terms of the dimensionless parameter λ/δ_n (static penetration depth/high frequency skin depth for normal electrons). Information on the band structure is implied, since for a given superconductor, experimental determination of λ/δ_n yields a value for m^*v_F, in which m^* is the effective mass of the normal electrons in the superconducting state and v_F is the Fermi velocity of these electrons.

* Supported in part by the Office of Naval Research.

GA2. Surface Impedance of a Superconductor in a Magnetic Field; Experiment.* M. S. DRESSELHAUS,† AND G. DRESSELHAUS, *Cornell University.*—A comparison has been made between the experimental data on tin at 1000 Mc/sec[1] and the two-fluid calculation of the magnetic field variation of the surface impedance. The Gorter-Casimir model is assumed for the normal electron concentration. The results in both longitudinal and transverse static magnetic fields imply that carriers of very small mass ($m^*/m \approx 10^{-3}$) are involved in the conduction processes in superconductors. A band structure for normal electrons in superconducting tin is proposed.

* Supported in part by the Office of Naval Research.
† National Science Foundation Postdoctoral Fellow.
[1] M. Spiewak, Phys. Rev. 113, 1479 (1959).

GA3. Use of Superconducting Transmission Line for Measuring Penetration Depths. D. R. YOUNG, J. C. SWIHART, S. TANSAL, AND N. H. MEYERS, *International Business Machines Corporation, Poughkeepsie.*—The penetration of the magnetic field into a superconducting film increases the inductance per unit length of a transmission line utilizing these films as conductors.[1] This effect is large if the line is properly designed. Measurements of the velocity of propagation in a line of this type can therefore be used to determine the penetration depth. Preliminary measurements have been made using a pulse technique. The experiment is being modified to use a resonant technique to increase the accuracy of the results and to permit studies of the effect of a magnetic field on the penetration depth. Solutions will be presented of London's equations for a film thickness comparable to the penetration depth.

[1] A. B. Pippard, Proc. Roy. Soc. (London) **A191**, 399 (1947).

GA4. Critical Field Curves of Mercury, Tin, and Indium.* D. E. MAPOTHER,† D. K. FINNEMORE, AND R. W. SHAW, *University of Illinois.*—Deviations from the law of corresponding states of the BCS theory are readily observed in precise measurements of the critical field curve. Most superconductors (including Sn and In) show a critical field which falls below a parabola drawn through H_0 and T_c, in general agreement with BCS. However, our measurements show Hg to be similar to Pb in showing a positive deviation from the parabolic relation. Given a reliable value of γ (the temperature coefficient of the normal electronic specific heat), the critical field data permit a precise determination of the temperature dependence of C_{es} (the superconducting electronic specific heat). The present work indicates an appreciable entropy contribution from the superconducting electrons at the lowest temperatures of observation (about 1.1°K), which makes the γ values uncertain. Thus significant comparisons of $C_{es}(T)$ for various elements by this method must await the extension of critical field measurements to temperatures well below 1°K.

* This work partially supported by the Office of Ordnance Research, U. S. Army.
† Alfred P. Sloan Foundation Fellow.

GA5. Superconductivity of Sigma, and Alpha Manganese Structures. R. D. BLAUGHER AND J. K. HULM, *Westinghouse Research Laboratories.*—The sigma and alpha manganese structures formed by binary alloys between the group (V, Nb, Ta, Cr, Mo, W) and the group (Mn, Fe, Co, Ni, Ru, Rh, Pd, Re, Os, Ir, Pt) were investigated for supercondictivity down to 1°K. Nineteen new superconductors were found in these two systems with the majority occurring in the sigma phase. A plot of superconducting transition temperature of the sigma phases against the average number of valence electrons per atom exhibited a maximum at approximately 6½ electrons per atom. This maximum is similar to those found for other structures by Matthias,[1] however it is displaced somewhat from the vicinity of 5 or 7 electrons per atom which Matthias indicated to be characteristic of other systems. The sigma phase data therefore suggests to us that in compound formation between pairs of transition elements, the *d*-band shape is preserved to some extent and is filled at an intermediate level by the available electrons.

[1] B. T. Matthias, *Progess in Low Temperature Physics* (North Holland Publishing Company, Amsterdam, 1957), Vol. II.

GA6. Isotope Effect in Superconducting Lead.* R. W. SHAW, D. E. MAPOTHER,† AND D. C. HOPKINS, *University of Illinois.*—The isotope effect has been remeasured in the range from T_c to 1.1°K using the same specimens previously described.[1] Near T_c, the data follow the mass dependence, $T_c \propto M^p$, where $p = -0.457 \pm 0.024$. This value is about nine percent lower than that previously reported,[1] and the difference is believed due to a uniform improvement in the chemical purity of all specimens. An exponent of -0.475 for Pb has been calculated theoretically.[2] Two specimens of nearly equal

average mass but with drastically different mass distributions were found to exhibit nearly identical critical field curves over the entire temperature range. In these measurements only the similarity principle remains anomalous. Of seven specimens measured, five show good approximations to similarity in their critical field curves. The remaining two, while similar to each other, disagree with the rest.

* This work partially supported by the Office of Ordnance Research, U. S. Army.
† Alfred P. Sloan Foundation Fellow.
[1] Hake, Mapother, and Decker, Phys. Rev. 112, 1522 (1958); 112, 1888 (1958).
[2] J. C. Swihart, Phys. Rev. 116, 45 (1959).

GA7. Superconducting Transition Temperature in Dilute Thallium Solid Solutions,* J. I. BUDNICK† AND D. J. QUINN, *IBM Research Laboratory, Poughkeepsie.*—A study of the variation of the superconducting transition temperature with composition in dilute thallium solid solutions has been made for several nonmagnetic solutes, namely, lead, indium, tin, and bismuth. All of these impurities produced a small increase (initially proportional to the concentration in the range from 0.01 to 0.1 atomic percent) in the superconducting transition temperature. The change in critical temperature at a fixed residual resistance ratio depends on the specific impurity added. This behavior is to be contrasted with the initial decrease in the transition temperature generally found by Serin,[1] Lynton, and co-workers when small amounts of nonmagnetic impurities were added to tin, aluminum, and indium.

* This work was supported in part by the Department of Defense.
† Now at IBM Watson Laboratory.
[1] G. Chanin, E. A. Lynton, and B. Serin, Phys. Rev. 114, 719 (1959).

GA8. Effect of Oxygen on the Critical Fields of Superconducting Tin Films.* HOLLIS L. CASWELL, *IBM Research Center, Poughkeepsie.*—Tin films of 4500 to 6000 A thickness have been evaporated through a glass mask onto room-temperature substrates of fused quartz at pressures less than 2×10^{-9} torr and in various partial pressures of oxygen by bleeding in reagent grade oxygen. The critical, external magnetic field extrapolated to 0°K required to switch a film from the superconducting to normal state as determined by the introduction of electrical resistance was found to increase from 380 oe for a pure film to 410, 500, 600, and 820 oe for films evaporated under conditions where the ratio of oxygen molecules to tin atoms striking the substrate was 1, 4, 7, and 10%, respectively. The effect is due to a decrease in surface mobility of tin atoms in the edges of the film. With pure films tin atoms in this region form discontinuous grains so that electrically the film appears to be of uniform thickness. Oxygen inhibits this breakup resulting in the formation of a continuous edge gradient whose thinner portions require higher switching fields. Mechanical removal of the edges reduces the field values to approximately that of a pure film.

* Supported in part by the Department of Defense.

GA9. Low-Temperature Thermal Conductivity of CaF_2 and MnF_2 Crystals. GLEN A. SLACK, *General Electric Research Laboratory.*—The thermal conductivity K of single crystals of CaF_2 and MnF_2 has been measured from 3°K to 300°K. Natural Ca and F are nearly isotopically pure; consequently, CaF_2 exhibits a true umklapp region where K rises exponentially from 0.12 watt/cm deg as the temperature decreases below 300°K. A maximum K of 30 watts/cm deg occurs at 12°K for a 0.3 cm diam sample. This maximum K is limited by about 100 ppm of impurities. A chemically pure crystal would have a maximum of about 100 watt/cm deg. The MnF_2 is tetragonal with $K_a=0.083$ watt/cm deg and $K_c=0.12$ watt/cm deg at 300°K. The ratio K_a/K_c increases toward unity at 14°K where a maximum K of 6 watt/cm deg is reached. MnF_2 possesses a para-antiferromagnetic transition at 68°K. No anomaly in K was observed at this Neel temperature, in contrast to the results on MnO.[1] The failure to observe a true umklapp region in isotopically pure MnF_2 is probably due to the 400-ppm residual impurity content.

[1] G. A. Slack and R. Newman, Phys. Rev. Letters 1, 359 (1958).

GA10. Thermal Conductivity in Dilute Solid Solutions of Cadmium Telluride in Mercury Telluride.* JOHN BLAIR, *MIT.*—The thermal conductivity in mercury telluride, and solid solutions of cadmium telluride in mercury telluride was measured from liquid nitrogen to room temperature. A theory of Callaway[1] was extended to cover the temperature range of measurements. The results are identical to those derived by Tavernier[2] from different considerations. The intrinsic thermal conductivity of pure mercury telluride was dominated by umklapp scattering, with a room-temperature value of 26 m watts/cm°K. The solid solution samples exhibited a T^{-1} dependence in the temperature range 100°K–200°K as predicted for mass fluctuation scattering with $T>\theta_D$. At higher temperatures, the thermal conductivity approached a $1/T$ dependence with a residual resistance due to mass fluctuation scattering in the presence of umklapp processes. The thermal conductivity of a 7% alloy at room temperature was 15 m watt/cm°K. The residual resistance ratio of two solid solution samples was computed using a result of Ziman. A satisfactory agreement was found between theory and experiment. The thermal conductivity ratio of solid solution samples in the T^{-1} region agreed strikingly well with the value calculated from theory using the mass fluctuation parameter of Tavernier.[2]

* Supported by Air Force Cambridge Research Center.
[1] J. Callaway, Phys. Rev. 113, 1047 (1959).
[2] J. Tavernier, Compt. rend. 247, 1179 (1958).

GA11. Thermal Expansion of Metals at Low Temperatures. P. G. KLEMENS, *Westinghouse Research Laboratories.*—The conduction electrons make a contribution to the coefficient of thermal expansion which is proportional to T. It can be shown by thermodynamic considerations that $d\Delta/dT=(dC/d\Delta)_T kV$, where Δ is the dilatation, C the electronic specific heat, V the volume and k the bulk modulus. This result differs slightly from one previously derived.[1] The electronic thermal expansion should be marked in transition metals and whenever the band structure is sensitive to the atomic volume. Olsen[2] deduced a value of $(1/C)(dC/d\Delta)_T$ of the order of +100 for aluminum from the strain dependence of the magnetic threshold curve, and measurements of the low-temperature thermal expansion could provide a check of this value.

[1] S. Visvanathan, Phys. Rev. 81, 626 (1951).
[2] J. L. Olsen, Helv. Phys. Acta 32, 310 (1959).

GA12. Specific Heat of Thorium at High Temperatures.* D. C. WALLACE, *Iowa State University.*—The specific heat and electrical resistivity of high-purity thorium have been measured from room temperature to 1000°C. The specific heat, which was measured by an electrical pulse-heating method,[1] increases from 6.56 cal/mole deg at 25°C to 9.54 cal/mole deg at 1000°C. The results have been analyzed in terms of additive lattice and electronic specific heats. The electronic properties of thorium have been discussed according to a qualitative, empirical band structure.

* Work done in the Ames Laboratory of the U. S. Atomic Energy Commission.
[1] Details of this method appeared in J. Appl. Phys. 31, 168 (1960).

MONDAY AFTERNOON AT 2:15

WSU McGregor Memorial

Conference Center Room B

(F. D. ROSI presiding)

Crystal Growth

H1. Initiation and Growth of Dendrites of Diamond-Lattice Materials. R. G. SEIDENSTICKER, J. W. FAUST, JR., H. F. JOHN, AND D. R. HAMILTON, *Westinghouse Research Laboratories.*—Billig,[1] Billig and Holmes,[2] and Bennett and Longini[3] have described the growth of long ribbon-like dendrites of germanium from undercooled melts. Recent observations indicate that a multi-twin structure is necessary for the propagation of dendrites of diamond-lattice materials. The morphology of the growth button which is formed when a seed crystal is placed in a supercooled melt is described for various twin configurations. The importance of having a twin configuration which is continuous across the width of the seed is pointed out. The lack of lateral continuity of the twin structure can prevent extension of dendritic growth into ribbon form.

[1] E. Billig, Proc. Roy. Soc. (London) **A229**, 346 (1955); Acta Met. **5**, 54 (1957).
[2] E. Billig and P. J. Holmes, Acta Cryst. **8**, 353 (1955); Acta Met. **5**, 53 (1957).
[3] A. I. Bennett and R. L. Longini, Phys. Rev. **116**, 53 (1959).

H2. Role of the Twin Plane in the Dendritic Propagation of Germanium Crystals. D. R. HAMILTON, R. G. SEIDENSTICKER, J. W. FAUST, JR., AND H. F. JOHN, *Westinghouse Research Laboratories.*—Dendrites of germanium exhibit preferred ⟨211⟩ growth directions and invariably contain a lamellar twin structure. The connection between these is examined. A model is proposed in which nucleation and growth occur in the 141° re-entrant corners formed by the operation of a twin plane on the {111} growth habit of germanium. It is shown that if only one twin plane is present, the crystal is not capable of indefinite ⟨211⟩ extension by nucleation and growth from re-entrant corners, since the corners grow out leaving a 219° ridge structure across which nucleation is difficult. If two twin planes are present, growth from one re-entrant corner serves to create a re-entrancy at the second twin plane at a location previously occupied by a ridge structure. The difficulty of nucleation across a ridge is thus circumvented in the two twinned crystal, which can never be entirely bounded by ridges. The doubly twinned crystal will be shown to possess easy growth in the six coplanar ⟨211⟩ directions as a consequence of its structure.

H3. Lateral Growth Processes in Dendrites of Diamond-Lattice Materials. H. F. JOHN AND J. W. FAUST, JR., *Westinghouse Research Laboratories* (introduced by R. L. Longini).—In the two preceding papers, it was shown that the longitudinal propagation of dendrites of diamond-lattice materials is dependent on the presence of a central twin structure containing two or more twin planes. The growth processes which widen the dendrite are more complex than those which lengthen it and are generally independent of the central twin structure. The dominant feature of the widening process is shown to be the outward growth of a pair of arms from each side of the central core which contains the twins. This gives, in cross section, an I-beam type of configuration. Freezing between these arms lags in varying degrees behind their outward growth. The places in which dislocation arrays can arise from this peculiar mode of growth are pointed out. The role of accretional growth layers in giving the final ribbon-like dendrite with its very smooth surface is briefly discussed.

H4. Dislocations in Dendrites. J. W. FAUST, JR., AND H. F. JOHN, *Westinghouse Research Laboratories* (introduced by C. Church).—John and Faust (previous abstract) showed that dislocations are introduced into dendrites by the trapping of molten germanium. In this paper more evidence will be given to support this model, and other aspects of dislocations will be taken up. The central stripe of dislocations, reported by Billig[1] and by Bennett and Longini,[2] is caused by the entrapment of liquid germanium within the dendrite. The position of these inclusions can be seen as raised hillocks on the unetched surface. The size of the hillocks depends on the size of the included droplets. Upon etching, these hillocks are found to be the sites of stars of dislocations. The stars have a core of very high density of dislocations and arms of shallow surface loops. Dislocations on the edges of the (111) faces may be either parallel or inclined to the central twin lamella, but never cross it.

[1] E. Billig, Proc. Roy. Soc. (London) **A229**, 346 (1955).
[2] A. I. Bennett and R. L. Longini, Phys. Rev. **116**, 53 (1959).

H5. Growth of Atomically Flat Surfaces on Germanium Dendrites. R. L. LONGINI, A. I. BENNETT, AND W. J. SMITH, *Westinghouse Research Laboratories.*—Dendrites of diamond-lattice semiconductors grow with extended flat {111} surfaces. It is suggested here that part of the liquid-solid interface is supercooled. New atomic planes are occasionally nucleated and rapidly grow across the supercooled region. When such a growing layer reaches the melt surface, it creates a step on the solid. It is proposed that the meniscus momentarily sticks to the corner of this step. Subsequent planes nucleated during this sticking period result in a step several atomic layers high, in accord with experiment. Elementary estimates of corner energy and amount of meniscus sticking yield results consistent with experiment.

H6. Liquid-Solid Interface Studies in Germanium Dendrites. A. I. BENNETT AND S. O'HARA, *Westinghouse Research Laboratories* (introduced by D. R. Hamilton).—In order to determine the structure of the liquid-solid interface in dendritic growth of Ge, apparatus was constructed for jerking a growing dendrite suddenly from the melt at high initial velocity and acceleration, estimated to be in excess of 250 cm sec^{-1} and 10^3 gravities, respectively. Several dendrites of various twin structures and impurity content, and with growth directions of both ⟨211⟩ and ⟨110⟩, were so jerked. Examination of the resulting structures disclosed some features apparently due to the freezing of a film of liquid which adhered to the solid on jerking, and other features apparently characteristic of the liquid-solid interface just prior to jerking. In several cases the flat {111} faces of the solid extended some distance below the melt surface; below the boundaries of these flats, the interface was curved, and thus thermally limited in growth. The structures observed support the growth mechanism proposed by John and Faust. Dendrites grown from very highly doped material show significant differences from pure samples.

H7. Study of Twin Boundaries as Recombination Centers in Germanium. J. P. MCKELVEY, *Westinghouse Research Laboratories.*—Carrier lifetime measurements in high-purity high-

lifetime Czochralski-type germanium crystals containing isolated twin boundaries have been made to determine to what extent such boundaries act as recombination centers. The continuity equation has been solved for the experimental geometry, and the solution allows one to account explicitly for the bulk lifetime and surface recombination velocity of the sample, and to express the recombination component at the twin boundary either as a recombination velocity or a recombination probability. Although grain boundaries representable as arrays of edge dislocations are known to act as strong recombination centers,[1,2] it is found that a twin boundary gives rise to little or no recombination. This effect is doubtless a consequence of the high symmetry of the twin configuration in the diamond lattice. Conservative upper limits of the twin recombination velocity of 100 ~m/sec in 10 ohm cm n-type and 30 cm/sec in near-intrinsic n-type germanium are arrived at. Results for p-type germanium and "double-twin" boundaries will be presented, and applications to dendritic crystals will be discussed.

[1] J. P. McKelvey, Phys. Rev. 106, 910 (1957).
[2] G. K. Wertheim and G. L. Pearson, Phys. Rev. 107, 694 (1957).

H8. Some Aspects of Ge Crystal Growth by Disproportionation of GeI_2. RALPH P. RUTH AND S. B. CATALANO, *Bendix Aviation Corporation* (introduced by William A. Smith).—Crystalline Ge layers have been prepared by epitaxy on single-crystal Ge substrate wafers, utilizing the disproportionation of GeI_2.[1] Layers up to 150 μ thick have been grown on p-type substrates having (111), (211), (311), (100), and (110) surfaces at average growth rates up to 15 μ/hr. The dependence of the growth rate upon temperature and other experimental conditions has been studied; the effects of these parameters and the crystalline orientation of the interface upon growth rate, degree of monocrystallinity, and conductivity type of the deposited layer have been evaluated with respect to the results of Newman and Wakefield.[2] X-ray diffraction examination, etching studies, and electrical measurements indicate that n-type single-crystal layers are usually formed on (211), (311), and (110) substrate planes, and n- or p-type single-crystal layers on (111) substrate planes. The structure and type of the deposit on (100) planes depends upon the growth rate and temperature involved. The results of some electrical measurements and impurity doping experiments will be described.

[1] Dunlap, Marinace, and Ruth, Bull. Am. Phys. Soc. Ser. II, 1, 294 (1956).
[2] R. C. Newman and J. Wakefield, International Conference on Solid State Physics in Electronics and Telecommunications, Brussels (June 2–7, 1958).

H9. Growth of Lead Telluride Crystals by the Czochralski Method. B. B. HOUSTON, *United States Naval Ordnance Laboratory*.—Growth of PbTe by the Czochralski method is difficult because of evaporation of the molten PbTe. An arrangement has been devised which partially overcomes this difficulty. In this arrangement the crystals are grown under an argon atmosphere. The system is static. Ordinary O-ring seals are used at locations which are at room temperature. Baffles in the region of high temperature-gradient impede the loss of material by convection. Crystals grown using this arrangement show considerable improvement over crystals grown by other methods. They have dislocation densities from 5 to 10×10^4/cm^2 and, in some cases, no small-angle boundaries. Crystals grown by the Bridgman method had $\sim3\times10^5$/cm^2 dislocations randomly distributed, plus small-angle boundaries separated on the average by 0.3 mm. Crystals grown from the vapor phase had similar densities of randomly distributed dislocations with small-angle boundary separations of 1.0 mm. We have grown crystals from melts with various Pb to Te ratios. Of these runs those which produced single crystals all resulted in p-type material with carrier concentrations of about 3×10^{18}/cm^3. We have also grown crystals from melts containing donor impurities.

H10. Infrared Measurements of Isotopic Oxygen Exchange Between Vitreous Silica and High Pressure Steam. W. G. SPITZER AND J. R. LIGENZA, *Bell Telephone Laboratories*.—When films of vitreous silica containing one type of oxygen isotope are exposed at elevated temperatures to high pressure steam containing a second oxygen isotope, some of the oxygen in the film is replaced by the isotope in the steam.[1] The concentration and distribution of the isotopes in the film can be determined from isotopic shifts of the silica infrared absorption bands. The films used were produced by the steam oxidation of oriented, single-crystal, oxygen-free silicon. Data will be presented for the time, temperature, and pressure dependence of the exchange process. The data fit an equation of the type $S=S_t(1-e^{-apt})$ where S is the observed shift, S_t is the total isotopic shift, p is the pressure, t is the time, and a is a constant independent of pressure and time but given by $a=(a_0/T)e^{-\Delta E/RT}$. The value of ΔE is 21.4 kcal/mole and a_0 is 1.03×10^5 atm^{-1} min^{-1} °K. S_t for the 9.2 μ absorption maximum is 0.4 μ when the oxygen isotopes 16 and 18 are used.

[1] J. R. Ligenza and W. G. Spitzer, J. Phys. Chem. Solids (to be published).

H11. Mechanism for the Isotopic Oxygen Exchange between Silica and High Pressure Steam. J. R. LIGENZA AND W. G. SPITZER, *Bell Telephone Laboratories*.—The model proposed for isotopic exchange is the solution of water in silica followed by a bimolecular reaction between the interstitial oxygen-18 water and Si-O^{16}-Si bond to form oxygen-16 water and Si-O^{18}-Si. The assumption that the reverse reaction between product species is negligible compared to the forward reaction is due to the rapid escape of oxygen-16 water into the gas phase and leads to an equation for the isotopic shift in the infrared absorption bands $S=S_t\{1-\exp[-(pk_0/RT)t\times\exp(-\Delta H-\Delta E_a/RT)]\}$, where S_t is the total isotopic shift, t is time, p is the steam pressure, k_0 is the specific bimolecular rate constant for exchange, ΔH is the heat of solution of water in silica, and ΔE_a is the activation energy for the exchange. The heat of solution is estimated to be 5.3 kcal/mole and the activation energy for exchange is 16.1 kcal/mole. The experimental k_0 is 8.5×10^{22} (molecules/cm^3)$^{-1}$ sec^{-1}. k_0 is calculated from absolute reaction rate theory by assuming a translating rotating water molecule reaction with an immobile Si-O-Si bond yields 3.3×10^{21} for k_0. The mechanism proposed for the isotopic exchange explains some of the features observed in the high pressure steam oxidation of silicon.

H12. Anisotropy of the Costa-Ribeiro Effect in Single Crystal Growth of Naphthalene.* S. MASCARENHAS AND L. G. FREITAS, *University of S. Paulo* (introduced by R. Smoluchowski).—The amount of charge trapped in an insulator during solidification is different for single and polycrystalline growth.[1] It was found that for a single crystal of naphthalene this effect depends also on the crystallographic orientation. In particular, growth normal to the cleavage plane gives 32×10^{-9} coulomb/g; growth along b gives 2.9×10^{-9} coulomb/g, and along a gives 2.5×10^{-9} coulomb/g. Thus the growth normal to the cleavage plane gives the highest values. All data were obtained for a material of 3×10^{-11} volt cm^{-1} residual conductivity at 90°C. An explanation of this effect, which depends upon impurity content, may be the existence of an anisotropic double layer at the solid-liquid interface. This may lead to a possible dependence of partition coefficients, which play a role, for instance in zone refining, upon the crystal orientation during growth from a melt.

* Supported by a contract with National Research Council of Brazil.
[1] S. Mascarenhas, thesis, University of S. Paulo (1958).

TUESDAY MORNING AT 9:30

Auditorium, Institute of Arts

(W. KOHN presiding)

DSSP Invited Papers

I1. Equilibrium Vacancy Concentrations in Silicon and Aluminum. R. W. BALLUFFI, *University of Illinois.* (30 min.)

I2. Magnetic Susceptibility of Excitons in Germanium. A. R. MOORE, *RCA Laboratories.* (30 min.)

TUESDAY MORNING AT 11:15

Auditorium, Institute of Arts

(CONYERS HERRING presiding)

Commemoration of Oliver Ellsworth Buckley. CONYERS HERRING, *Bell Telephone Laboratories.*

Oliver E. Buckley Lecture

I3. Magneto Spectroscopy in Semiconductors. BENJAMIN LAX, *Lincoln Laboratory.* (45 min.)

Business Meeting of the Division of Solid State Physics

TUESDAY MORNING AT 9:30

Lecture Hall, Institute of Arts

(J. W. CLELAND presiding)

Irradiation Effects: Compounds

IA1. Threshold Energy for Lattice Displacement in α-Al_2O_3. GEORGE W. ARNOLD, *United States Naval Research Laboratory.*—Levy and Dienes[1] have shown that reactor irradiation of α-Al_2O_3 causes the growth of an optical absorption band at 205 mμ which cannot be generated by x rays or γ irradiation. This band is presumed to arise from the trapping of charges at defects which occur when atoms are displaced. Samples of α-Al_2O_3 were irradiated at 77°K with fast electrons and the resulting optical absorption measured without warmup. Irradiation at 77°K produces many more centers than does a comparable irradiation at room temperature, the ratio of the yields at these two temperatures being at least ten. The experimental values at various electron energies are best fitted by the theoretical cross-section curve for $E_d = 50(\pm 5)$ ev in the case of aluminum and by $E_d = 90(\pm 5)$ ev in the case of oxygen. No unequivocal assignment of the defect can be made but aluminum displacements might be more likely because they have greater freedom of movement. Oscillator strengths are obtained of $f = 0.51$ and $f = 1.02$ if the defect arises from an aluminum or from an oxygen displacement, respectively.

[1] P. W. Levy and G. J. Dienes, *Report of Bristol Conference on Defects in Crystalline Solids July, 1954* (The Physical Society, London, 1955), p. 256.

IA2. Effect of Reactor Irradiation upon Hydrogen Adsorption by an Alumina Catalyst.* D. B. ROSENBLATT,† G. J. DIENES, AND J. C. ROTHMANN,† *Brookhaven National Laboratory.*—Recent studies of alumina catalysts have shown that their activity may be enhanced by prior exposure to radiation.[1,2] Gas adsorption studies may shed some light on the mechanisms leading to this enhancement. Hydrogen adsorption isotherms at 78°K were obtained for unirradiated and irradiated γ-Al_2O_3 powder by admitting known quantities of the pure gas into a constant volume apparatus. The irradiations were carried out in the Brookhaven reactor at 50°C in evacuated quartz ampules to doses of approximately 10^{18} neutrons/cm^2. Langmuir's relation was obeyed both before and after irradiation up to pressures of 150 mm of Hg, but the constants of the equation were altered significantly by the irradiation. There was no radiation effect upon the specific surface areas, which were about 85 m^2/g as obtained by the B.E.T. analysis using nitrogen at 78°K.

* Work supported under the auspices of the U. S. Atomic Energy Commission.

† Guest Scientists from Frankford Arsenal.

[1] H. W. Kohn and E. H. Taylor, J. Phys. Chem. **63**, 500 (1959).

[2] Maurin, Ballantine, and Sucher, Brookhaven National Laboratory 3786 (1958).

IA3. Annealing of Neutron Irradiated GaAs.* L. W. AUKERMAN, R. GRAFT, AND P. C. PETERS,† *Battelle Memorial Institute.*—Changes in resistivity and Hall coefficient of *n*-type GaAs which had been irradiated with fast neutrons were studied as a function of annealing temperature and time. For a given stage of annealing, the recovery of the resistivity is more complete than the recovery of the Hall coefficient. Isochronal annealing experiments indicate two types o[f]

behavior: Type I shows at least two distinct annealing regions located at about 270–350°C and 430–500°C; and type II shows gradual annealing over the entire range 270–500°C. The activation energy for type I annealing is about 4.5 ev at 460–500°C, and for type II about 2.9 ev at 400–440°C. The specimens do not completely recover at 500°C. The two types of annealing appear to be correlated to the amount of irradiation and possibly to the total impurity content. The large activation energy for recovery, and the different types of behavior, are possibly explained in terms of trapping centers for the mobile defect.

* Supported by the Aeronautical Research Laboratory, Wright Air Development Center.
† Battele Summer Program Student—now at Purdue University.

IA4. Effect of γ Irradiation on Thermoelectric Power of Bismuth Telluride.* ROBERT A. ARTMAN,† *Bucknell University* AND A. N. GOLAND,† *Brookhaven National Laboratory.*—Measurements of changes produced in thermoelectric power and electrical conductivity of *n*- and *p*-type polycrystalline bismuth telluride and bismuth by γ irradiation from Co^{60} have been made. *N*-type samples measured *in situ* at room temperature show a thermoelectric power and conductivity which decrease with irradiation. The effect saturates at less than 6×10^6 r and anneals out in less than 3 hr. Near dry-ice temperatures the thermoelectric power increases with irradiation. The initial rate of increase is approximately 2% per 10^6 r. The increase anneals out with a half life of 29 hr at 230°K. Conductivity decreases approximately 1% for a dose of 6.8×10^6 r. *P*-type samples near dry-ice temperatures show thermoelectric power also increasing with irradiation. The initial rate of increase matches that of the *n*-type. No data were taken on the annealing rate. The conductivity shows an increase of less than 0.2% for a dose of 25.2×10^6 r. Generally irradiation has the same effect upon thermoelectric power as increasing the temperature. Bismuth shows no change in thermoelectric power near dry-ice temperature for a dose of 12.4×10^6 r.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Visiting Scientist at Brookhaven National Laboratory, Summer, 1959.
‡ Guest from Ordnance Materials Research Office, Watertown, Massachusetts.

IA5. Radiation Effects on Thermoelectric Power in Bi_2Te_3. R. A. LEVY,* *U. S. Naval Radiological Defense Laboratory.*—Samples of *n*-type Bi_2Te_3 obtained from Merck, Inc., have been bombarded with 2-Mev electrons from a Van de Graaff accelerator in beam currents ranging from 1 to 85 μa. Total dosages ranged up to 100 μamp-hr. Thermoelectric power and resistivity measurements were made before, during, and after radiation by means of standard dc techniques using Chromel-Alumel thermocouples. Thermoelectric power decreased up to 50% during bombardment and recovered afterward. Temperature effects prevented an adequate determination of the effect of radiation on electrical resistivity. Other than surface oxidation or melting from the high temperatures produced by the bombarding electrons, no permanent effects were observed in the samples. All measurements were made on flat rectangular wafers sliced parallel to the axis of polycrystalline cylindrical ingots.

* Present address: Hughes Aircraft Company, Newport Beach, California.

IA6. Effect of Reactor Irradiation on Thermoelectric Properties of PbTe and Bi_2Te_3. J. C. CORELLI, R. T. FROST, AND F. A. WHITE, *Knolls Atomic Power Laboratory.**—Specimens of commercially available PbTe and Bi_2Te_3 have been irradiated at a temperature of 60±20°C to a total flux-time of $1.0\pm0.3\times10^{19}$ cm^{-2} of neutrons having energy greater than 1 Mev. Duplicate samples irradiated with and without cadmium shields allowed a search for effects of transmutations caused by an integrated thermal neutron flux-time of $1.5\pm0.5\times10^{20}$ cm^{-2}. Preliminary comparison of Hall coefficients of irradiated and unirradiated *n*-type PbTe indicates a decrease in carrier concentration by a factor 4.5±0.5. Seebeck coefficients at 30°C of *n*- and *p*-type PbTe and *n*-type Bi_2Te_3 increased by factors of 1.8, 1.6, and 1.1, respectively, with no significant differences observable between cadmium shielded and unshielded specimens. The *p*-type Bi_2Te_3 (no initial impurity doping) exhibited an *n*-type Seebeck coefficient subsequent to the irradiation, and its magnitude was changed by a factor of 0.7 for the shielded and 1.8 for the unshielded specimen. The room temperature electrical resistivity of shielded and unshielded *n*-type PbTe increased by a factor of 10 as a result of the irradiation. Additional measurements of electrical resistivities and Seebeck coefficients at higher temperatures will be presented.

* Operated by the General Electric Company for the U. S. Atomic Energy Commission.

TUESDAY MORNING AT 9:30

WSU McGregor Memorial

Conference Center Room B

(H. PALEVSKY presiding)

X-Ray and Neutron Scattering

J1. Diffusive Motions in Water and Cold Neutron Scattering.* K. S. SINGWI AND ALF SJÖLANDER, *Argonne National Laboratory.*—By using a model of liquid water in which a molecule executes an oscillatory motion for a mean time τ_0, then diffuses by continuous motion for a mean time τ_1, and then repeats this sort of motion, the differential scattering cross section for cold neutrons has been calculated. The general formula for the broadening of the "quasi-elastic" component of the scattering reduces in case (i) $\tau_1\gg\tau_0$, to the simple diffusion broadening, $\Delta\epsilon=2\hbar K^2D$; and in case (ii) $\tau_1\ll\tau_0$, to $\Delta\epsilon=2\hbar/\tau_0\{1-\exp(-2W)/(1+K^2D\tau_0)\}$, where $2W$ is the Debye-Waller factor, $K\hbar$ is the momentum transfer and D is the diffusion coefficient. The experimentally observed value of the broadening by Hughes *et al.*[1] ($\Delta\epsilon\leqslant3\times10^{-3}$ ev, for neutrons of incident energy 5.2×10^{-3} ev) can be explained by the formula of case (ii), if we assume for τ_0 a value $\geqslant4\times10^{-13}$ sec. This time seems to be consistent with other independent experimental observations. For $K^2D\tau_0\ll1$, the broadening in case (ii) reduces to that in case (i), and for $K^2D\tau_0\gg1$, it approaches the asymptotic value $2\hbar/\tau_0$. Also the broadening in case (ii), as opposed to that in case (i), is rather insensitive to the scattering angle. These features of the broadening need experimental verification.

[1] D. J. Hughes, H. Palevsky, W. Kley, and E. Tunkelo, Phys. Rev. Letters 3, 91 (1959).
* Based on work performed under the auspices of the U. S. Atomic Energy Commission.

J2. Application of Tamm-Dancoff Approximation to the Problem of Elastic X-Ray Scattering in Infinitely extended Crystal. T. T. KIKUCHI AND H. EKSTEIN,* *Armour Research Foundation.*—The Tamm-Dancoff approximation is used to derive a form of von Laue's dynamical equations[1] for x-ray diffraction from the time-independent nonrelativistic Schrödinger equation describing a system consisting of infinitely extended crystal interacting with photons. It is found that the probability amplitudes for finding the crystal in the ground state in the presence of a photon with a particular polarization follow the same relationship as the Fourier coefficients of the displacement vector in the classical derivation.[2] In the present analysis, the inelastic scattering process, nuclear motion, and the higher radiative correction beyond the dispersion terms are neglected.

* Now at Argonne National Laboratory, Lemont, Illinois.
[1] M. von Laue, *Röntgenstrahlinterferenzen* (Edwards Brothers, Inc., Ann Arbor, Michigan, 1943), 313 pp.
[2] W. H. Zachariasen, *Theory of X-Ray Diffraction in Crystals* (John Wiley & Sons, Inc., New York, 1945), 113 pp.

J3. $M_{2,3}$ Valence Band Emission Spectra of Iron, Cobalt, and Nickel.* D. H. TOMBOULIAN AND D. E. BEDO, *Cornell University.*—Unpublished measurements on the relative intensity distributions of the valence $\rightarrow 3d$ emission spectra of the ferromagnetic group of metals have been reduced making use of recent information on the shape of the underlying continuum as determined by a systematic study[1] of the bremsstrahlung emitted by targets bombarded by low energy electrons. The features of the $I(E)/\nu^3$ distributions for the bands are sensitively dependent on the scheme adopted for removing the contribution coming from the continuum. It is believed that the present approach yields reliable results as to the intensity contour of the characteristic spectra. Photon energies in ev corresponding to the peaks of the bands are 51.3, 57.8, and 64.8 for Fe, Co, and Ni, respectively. The high-energy limits in ev of the bands emitted by the metals (in the order cited) occur at 56.5, 61.4, and 68.9. The associated low-energy limits are observed to be at 42.0, 40.6, and 60.0 ev. Comparison will be made with absorption data and other investigations of the emission bands.

* Research supported by the Office of Ordnance Research, U. S. Army.
[1] T. J. Peterson and D. H. Tomboulian, Bull. Am. Phys. Soc. Ser. II, 4, 419 (1959).

J4. A Variational Principle for Scattering.* G. H. GOEDECKE AND E. BROWN, *Rensselaer Polytechnic Institute.*—A variational principle is developed for elastic particle scattering by potentials of finite range. A positive-definite functional, equal to the squared magnitude of an error function integrated over the region of nonzero potential, is minimized with respect to parameter variations in the trial wave function. The technique differs from others in that it is a minimum principle, and it requires trial functions defined only inside the potential. Partial wave numerical calculations are made for a square well potential of depth U_0, radius a, such that $U_0a^2=0.64$, using atomic units. Power series radial trial functions, of cubic degree or less, yield scattering amplitude coefficients which are in excellent agreement with those obtained by the exact phase shift method, for a choice of energies $ka=0.6$ and $ka=7.0$. Further work will be reported.

* Supported by the U. S. Atomic Energy Commission.

J5. Measurement of the X-Ray Atomic Scattering Factors of Iron and Copper. DAVID R. CHIPMAN, *Watertown Arsenal,* AND BORIS W. BATTERMAN, *Bell Telephone Laboratories.*—Measurements of the scattering factors of iron and copper were recently reported[1,2] in the literature in an attempt to provide some information on the distribution of $3d$ electrons in the metallic states of these elements. Since the reported measurements were not consistent with one another, we have attempted to repeat these measurements choosing experimental parameters to minimize the corrections in reducing the experimental x-ray intensities to atomic scattering factors. We have measured the integrated intensities of copper and iron powders with monochromatic Mo$K\alpha$ radiation. Extensive tests were made which established that surface roughness, preferred orientation and extinction effects were negligible. The relative intensities of the lowest order copper and iron reflections gave a ratio of experimental atomic scattering factors in good agreement with values calculated for the free atom and confirm the experimental ratio previously measured[2] with monochromatic Fe$K\alpha$ radiation. However, an absolute standardization of the x-ray intensity is necessary to unambiguously define the electron distribution in any single element. We are therefore reducing the relative intensities of iron and copper to absolute values by directly measuring the intensity of the primary beam.

[1] R. J. Weiss and J. J. De Marco, Revs. Modern Phys. 30, 59 (1958).
[2] B. W. Batterman, Phys. Rev. 115, 81 (1959); Y. Komura, Y. Tomiie, R. Nathans, Phys. Rev. Letters 3, 268 (1959).

J6. Atomic Scattering Factor in Iron. FRANK STERN, *United States Naval Ordnance Laboratory.*—Independent calculations by the author[1] and by Wood[2] show that wave functions near the bottom of the $3d$ band in metallic iron have more diffuse charge distributions than do wave functions near the top of the band. This reduces the atomic scattering factor, f, for a partially filled $3d$ band below the value one might otherwise expect. Values of f for the charge distributions characteristic of the top and bottom of the $3d$ band in metallic iron will be presented, as will scattering factor values for self-consistent $3d$ wave functions without exchange for the $3d^64s^2$, $3d^74s$, and $3d^8$ configurations of atomic iron.[3] Scattering factors for the ground configuration of atomic iron based on wave functions with exchange have recently been published by Freeman and Wood.[4]

[1] F. Stern, Phys. Rev. 116, No. 6 (to be published).
[2] J. H. Wood, MIT Solid State and Molecular Theory Group Quarterly Progress Report No. 34, October 15, 1959 (unpublished).
[3] F. Stern, Phys. Rev. 104, 684 (1956).
[4] A. J. Freeman and J. H. Wood, Acta Cryst. 12, 271 (1959).

TUESDAY MORNING AT 9:30

Auditorium, Rackham Memorial

(WILLIAM C. OVERTON presiding)

Elastic Properties

JA1. Elastic Constants of Hexagonal Cadmium Sulfide. D. I. BOLEF, N. T. MELAMED, AND M. MENES, *Westinghouse Research Laboratories.*—The adiabatic elastic constants of a single crystal of hexagonal cadmium sulfide were measured at $T=27$°C. The crystal was grown commercially by vapor deposition and was large enough to permit exposure of three

sets of plane parallel faces having a sufficient area for the determination of the five elastic constants. For the three directions of sound propagation the acoustic path lengths were: $\|c$ axis, 2.0222 cm; $\|a$ axis, 2.4065 cm; 45° to c axis, 2.0945 cm. The crystal orientations, determined by x-ray diffraction, were known to ±2°. Measurements were made at 10 Mc by means of an ultrasonic cw mechanical resonance technique. With this technique, the end corrections due to the transducer and bond could be accurately calculated. The ultrasonic pulse-echo technique was used to check the cw results. The elastic constants, in units of 10^{11} dynes/cm², are

c_{11}	c_{33}	c_{44}	c_{13}	c_{12}
8.432	9.397	1.489	5.212	4.638.

The estimated limits of probable error do not exceed 0.2% for all but c_{13}. For c_{13} the probable error is 1.3%. The internal consistency, obtained by measuring the same elastic constant in different crystalline directions, was 0.1%. The elastic constants were calculated from the observed velocities using the theoretical density of $\rho=4.823$ g/cc obtained from unit cell dimensions and atomic weight.

JA2. Elastic Constants of Palladium from 4.2–300°K. J. A. RAYNE, *Westinghouse Research Laboratories* (introduced by M. A. Biondi).—Elastic constant measurements have been made on a single crystal of palladium in the temperature range 4.2–300°K. Extrapolation of the data to absolute zero gives

$$c_{11}=2.341\pm0.027\times10^{12}\text{ dyne cm}^{-2},$$
$$c_{12}=1.761\pm0.027\times10^{12}\text{ dyne cm}^{-2},$$
$$c_{44}=0.712\pm0.003\times10^{12}\text{ dyne cm}^{-2}.$$

The corresponding value of Debye temperature is $\theta_0=275\pm8$°K, which compares well with the calorimetric figure[1] of $\theta_0=274\pm3$°K. Both shear constants show an anomalous temperature dependence. This dependence can be correlated with the temperature variation of the contribution to C and C', resulting from the presence of holes in the d band of palladium.

[1] B. Yates and F. E. Hoare, Proc. Roy. Soc. (London) **A140**, 42 (1957).

JA3. Low Temperature Elastic Constants of Vanadium. G. A. ALERS, *Ford Motor Scientific Laboratory*.—The phonon frequency distribution of vanadium has been measured by slow neutron scattering.[1] It is therefore important that the elastic constants be determined so that the distribution may be calculated using theories of lattice dynamics. Two cylindrical single crystal specimens with their lengths parallel to the [100] and [110] crystal axes were prepared by D. K. Donald of this laboratory using a floating zone technique. As determined by the ultrasonic pulse technique, the directly measured elastic moduli are, in units of 10^{11} dynes/cm²,

	4.2°K	77°K	300°K
C_{11}	23.24	23.17	22.79
C_{44}	4.60	4.52	4.25
$\frac{1}{2}(C_{11}-C_{12})$	5.65	5.63	5.46.

The room temperature results agree with another recent determination.[2] The 4.2°K results determine a Debye temperature of 399.3°K. This disagrees with the value of 338°K determined by calorimetry[3] but is in better agreement with the value of 375°K obtainable from the neutron scattering data.

[1] Eisenhauer, Pelah, Hughes, and Palevsky, Phys. Rev. **109**, 1046 (1958).
[2] D. I. Bolef and M. Menes (private communication).
[3] Corak, Goodman, Satterthwaite, and Wexler, Phys. Rev. **102**, 656 (1956).

JA4. Elastic Constants of Bismuth. Y. ECKSTEIN,* A. W. LAWSON, AND D. H. RENEKER,† *University of Chicago*.—Preliminary values of the adiabatic elastic constants of bismuth at 25°C have been determined by measuring the longitudinal and transverse velocities of sound along five orientations. The values in dynes/cm² are $c_{11}=61.7\times10^{10}$, $c_{44}=10.74\times10^{10}$, $c_{66}=18.79\times10^{10}$, $c_{33}=36.3\times10^{10}$, $c_{14}=-6.92\times10^{10}$, $c_{13}=23.8\times10^{10}$. These values of the elastic constants are appreciably different from those calculated from the statically determined values of Bridgman. The latter are believed to be in error. The precision as yet is not high enough to permit a decisive statement concerning the applicability of the Laval-Raman theory.

* Bell Telephone Predoctoral Fellow.
† National Science Foundation Pre-doctoral Fellow, now at du Pont Experimental Station, Wilmington, Delaware.

JA5. Elastic Moduli of Lead. D. L. WALDORF, *Ford Motor Scientific Laboratory* (introduced by G. A. Alers).—Accurate values of the elastic moduli of lead are particularly important to investigations of specific heat and to theories of lattice dynamics. It was necessary to use somewhat special techniques to prepare the (110) oriented samples which are necessary for the pulse-echo technique. A very pure lead crystal exhibits high ultrasonic attenuation which is produced by dislocation damping. The addition of 0.1 atomic percent Bi reduced this attenuation by pinning down the dislocation loops and made possible reliable measurements. The moduli, in units of 10^{11} dynes/cm², are

T	$\frac{1}{2}(C_{11}+C_{12}+2C_{44})$	C_{44}	$\frac{1}{2}(C_{11}-C_{12})$
300°K	6.155	1.505	0.368
4.2°K	7.049	1.958	0.510.

These are accurate to 1% and compare favorably with the early work of Goens.[1] A value for the Debye temperature of 105°K was calculated from the 4.2°K moduli.

[1] E. Goens, Ann. Physik **38**, 456 (1940).

TUESDAY MORNING AT 9:30

WSU Community Arts Auditorium

(D. TURNBULL presiding)

Mostly Noncrystalline Solids

K1. Structural Interpretations of the Properties of Oxide Glasses. HENRY H. BLAU, *The Ohio State University and The Federal Glass Company*.—The Zachariasen-Warren network concepts of glass structures may still be used to obtain quantitative interpretations of the properties of oxide glasses. An approach is derived on the basis of the relative number and arrangements of bridging and nonbridging oxygen ions to show the relations of such properties as density, coefficient of expansion, and vapor pressure to composition and structure. Inconsistencies of previous interpretations are brought out

by adducing data for additional systems and ranges of compositions. There are indications of the possibilities that the network may become more condensed as network modifiers are added to the structure. The relation of adjustments of structure and properties as the result of the redistribution of nonbridging oxygens on heat treatment is also discussed.

K2. Mechanism of Indentation Formation in Rigid Glass. WILLIAM B. HILLIG, *General Electric Research Laboratory* (introduced by Gerald W. Sears).—The flow mechanism of "rigid" glass under conditions of a Vickers diamond pyramid hardness test has been investigated using vitreous silica. The observed final mean pressure under the indenter of 7×10^4 atm, is only slightly greater than the maximum observed compressional stress in a fiber bent into a loop. Yet no permanent deformation occurs in the fiber. The indentation area was found to be essentially proportional to the load between 50 g and 800 g, as expected from geometric similitude considerations. No residual strain birefringence was detected. However, the refractive index n was altered from its bulk value. In isochronal heating experiments, n relaxed to its normal value above 800°, and the maximum shrinkage of the indentation occurred at 800–900°. The temperature rise during indentation is calculated to be of order 10^3 degrees. Neither of the previously proposed mechanisms of Bastick and Douglas, respectively, involving temperature rise or viscous flow at ultra-high shear, completely account for the observations. Rather, the results imply that the compressed glass structure under the indenter has an intrinsically greater fluidity than the normal glass, modifying the previous interpretations.

K3. Determination of Randomness in Silica Glass by Gaseous Diffusion. KENNETH B. MCAFEE, JR., *Bell Telephone Laboratories.*—A measure of the randomness in the structure of a glass such as silica may be determined by a detailed study of the effects of temperature and radius of the diffusing atom. Observations of the diffusion constant, D, of helium in silica glass over a very wide temperature range (1300°K to 79°K) have yielded a straight line in D vs $1/T$ plot but with slight deviations at extremely low temperature. Examination of these data in the light of the theory of random flights permits a close estimate of the variation in barrier heights itself. Measurements have also been made of the variation of D for helium, hydrogen, deuterium, and neon. The lack of randomness is indicated strongly by the fact that hydrogen which is only 0.24 A larger in effective diffusing radius than helium diffuses 1000 times slower. Combining these two results we have determined that the degree of randomness in barrier heights for diffusion in silica glass is less than a very few percent indicating that the structural randomness itself must also be very small. These results will be related to the random-network concept of the glass state.

K4. Glass Transformation Behavior of Selenium. A. B. BESTUL, *National Bureau of Standards.*—A glass transformation temperature for selenium may be determined from the demarcation between the volume-temperature relation for the equilibrium supercooled liquid and that for a commonly formed glass. This demarcation occurs around 30°C. We have investigated how much this temperature can be shifted by varying the rate of temperature change during its determination and by heat treatment of the glass in the temperature region immediately below the transformation temperature, (annealing). Within the range of cooling rates practicable for laboratory glass transformation temperature determinations, values were obtained over the temperature range from 28.2° to 30.7°C. By annealing about a month around 20°C, the existence of the equilibrium supercooled liquid at a temperature as low as 22°C was demonstrated. Transient deviations from the equilibrium supercooled liquid were observed at temperatures up to about 42°C. This range from 22 to 42°C may be compared with the range from 20 to 45°C reported as the *Einfrierberich* for selenium by Ueberreiter and Orthmann[1] on the basis of viscosity measurements. Within this region the same particular forms of the volume-temperature relation are found for selenium as have been found for certain other glasses and explained as relaxation toward the equilibrium supercooled liquid.

[1] K. Ueberreiter and H. J. Orthmann, Koll. Z. **123**, 84 (1951).

K5. Diffusion Coefficients of Helium in Fused Quartz. R. C. FRANK, R. W. LEE, AND D. E. SWETS, *General Motors Research Laboratories.*—The diffusion of helium through the walls of high purity fused quartz hollow cylinders was studied using a mass spectrometer as a detecting device. By surrounding the thin cylinder with helium and observing it diffuse through into the mass spectrometer, permeation rates and diffusion coefficients were measured in the temperature range of 24°C to 1040°C. The diffusion coefficients were measured from the transient effect and both the "time lag" and "decay curve" methods were used to calculate the diffusion coefficient values. The agreement between the two sets of values indicates that the diffusion process is relatively simple. As suggested by Jones[1] and others, the diffusion behavior is slightly different in the temperature range of 24°C to 200°C than it is in the range of 300°C to 1040°C. In the low temperature range the activation energy for diffusion is 5600 cal/g atom and in the higher range it is 5600 cal/g atom. The heat of solution is negative in both ranges and is apparently smaller at low temperatures than at high temperatures.

[1] W. M. Jones, J. Am. Chem. Soc. **75**, 3093–3096 (1953).

K6. Molecular Beam Investigation of Energy Exchange between a Gas and a Solid.* J. H. MCFEE AND P. M. MARCUS, *Carnegie Institute of Technology.*—A beam of potassium atoms with thermal energies was reflected from various solid surfaces, and the velocity distribution of the reflected atoms measured with a precision mechanical velocity selector. The surfaces investigated included polycrystalline Cu, W, Au, and cleavage planes of MgO and LiF crystals. Surface temperatures ranged from 500° to 2100°K. Beams reflected from Cu, W, Au, and MgO were found to have highly Maxwellian distributions characterized by the measured surface temperatures (only the Cu surface temperature was accurately measured). The reflection from LiF was anomalous. The velocity distributions were non-Maxwellian at high reflector temperatures. Changing the temperature of the incident beam caused a change in the temperature[1] of the reflected beam. From the observed temperature change, the accommodation coefficient is estimated to be 0.7 ± 0.1 for surface temperatures in the range 600°K to 900°K. The shape of the measured distributions cannot be approximated by a linear superposition of Maxwell curves corresponding to the incident beam and reflector temperatures.

* Supported by Office of Naval Research.
[1] "Temperature" assigned by fitting Maxwell curve to a portion of measured distribution.

TUESDAY MORNING AT 9:30

WSU McGregor Memorial

Conference Center Room L

(V. W. MILES presiding)

General Physics

KA1. Angular Correlation of the 1.07–1.24-Mev Gamma Cascade in the Decay of Ga^{68}.* M. K. RAMASWAMY AND P. S. JASTRAM, *The Ohio State University.*—We have measured the angular correlation of the 1.07–1.24-Mev gamma-ray cascade in Zn^{68} following the decay of 68-min Ga^{68}. The Legendre polynominal expansion coefficients were determined to be $A_2=0.31\pm0.03$ and $A_4=0.23\pm0.07$. The measured correlation establishes the spin sequence to be 2–2–0, with a quadrupole-dipole mixing ratio δ of $+1.8\pm0.2$ for the 1.24-Mev gamma ray. The result of the angular correlation work together with the allowed nature ($\log ft=5.7$) of the electron-capture decay to the 2.3-Mev level fixes the spin and parity of this level to be 2^+. The results are consistent with the near-harmonic model of Scharff-Goldhaber and Weneser[1] for even-even nuclei.

* Supported by the U. S. Atomic Energy Commission.

[1] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).

KA2. Dielectric Relaxation Functions. SIVERT H. GLARUM,* *Brown University.*—The dielectric relaxation behavior of many simple substances is frequently described by a continuous distribution of relaxation times. Attempts to interpret this behavior in terms of a corresponding distribution of first-order rate processes have not generally been successful. It is proposed that a relatively simple process, not first order in time, is responsible for such behavior. As an example, a defect-diffusion model is cited. This model implies that the relaxation of a molecule is more probable immediately after one of its neighbors has relaxed than at an arbitrary time. The motion of a relaxing site or defect is described by a diffusion equation, and, under the appropriate conditions, distributions of relaxation times are predicted which closely resemble the skewed-arc and circular-arc distributions found for many dielectrics.

* Present address: Bell Telephone Laboratories.

KA3. Theory of Vibrational Emission in Shock Waves.* J. C. DECIUS, *Oregon State College.*—In a recent work[1] the emission of the first overtone of CO has been observed and the vibrational relaxation time deduced from the time dependence using a three-state model. Since it has not yet been feasible to observe the transitions $2\rightarrow0$, $3\rightarrow1$, etc., separately, it is pertinent to sum the intensity of all such unresolved components. The assumption that excitation by collision is a one-quantum process combined with a solution[2] for the kinetics of the complete set of harmonic oscillator levels leads to the result that

$$I^{(n)}=I_\infty^{(n)}\{1+[I_0^{(n)}-I_\infty^{(n)}/I_\infty^{(n)}]e^{-\lambda t}\}^n,$$

where $I^{(1)}$ and $I^{(2)}$ are the total emission, respectively, for a fundamental and an overtone transition; in each case $\lambda=[1-\exp(-h\nu/kT_\infty)]/\tau_{10}$, where τ_{10} is the collisional deactivation time for the process $1\rightarrow0$.

* Supported by the Office of Naval Research.

[1] Windsor, Davidson, and Taylor, Seventh Symposium on Combustion (London, 1958), p. 80.

[2] E. W. Montroll and K. W. Shuler, J. Chem. Phys. **26**, 454 (1957).

KA4. Erosion of Meteorites and the Lunar Surface by Sputtering. L. REIFFEL, *Armour Research Foundation.*—Solar plasma streams containing protons of a few kilovolts energy with an admixture of helium and heavier ions have presumably been bombarding the lunar surface and interplanetary debris for times of the order of 10^9 yr. Sputtering of solid surfaces exposed to such streams is discussed in terms of yields expected and erosion rates produced. While sputtering data on minerals such as olivine are not yet available, it seems likely that the small scale structure (meters) of the lunar surface has been markedly altered by sputtering. Proton sputtering rates for iron meteorites have been used by Whipple to establish hydrogen densities in space. Calculations are presented which suggest that solar helium rather than hydrogen may dominate sputtering of both the lunar surface and meteorites. Additional laboratory data are urgently required for both metals and mineral-like substances.

KA5. Some Characteristics of Matter in Space.* BERTRAM DONN, *National Aeronautics and Space Administration.*—Certain inferences about matter in space may be drawn from recent comet and meteor studies. It is now generally established that nearly all meteors are of cometary origin and that meteors are fragile, porous objects. We adopt Whipple's icy conglomerate model of the comet nucleus, modified to include a significant fraction of reactive molecules as an important energy source. For a 10-km radius, a self-consistent model has the following properties: Mass $\sim10^{18}$ g; central pressure $\sim10^3$ dynes/cm^2; surface gravity ~0.1 cm/sec^2; density ~0.1 g/cm^3; temperature $\lesssim200$°K. No chemical processes occur in the interior but vaporization and recondensation continuously occurs. The latter process may have some effect on the structure of meteoric particles embedded in the volatile matrix. We conclude that meteoric particles were collected by growing comets and retained in them with little change until released. Such small, irregular objects are generally consistent with recent work on particle growth. Spherical iron particles collected in the atmosphere or in sediments are not likely to be original material from space. Experimental studies are suggested by this investigation.

* Supported in part by the National Science Foundation.

KA6. Triondynamics and Thermonuclear Experiments. JOSEPH G. BARREDO, *C.S.I.C.*—The chronosuperconductivity effect, in which triondynamics is based, was demonstrated previously[1] for sweep-times of 10^{-8} sec/cm, and rise-times of $7\cdot10^{-9}$ sec, and redemonstrated now (with a sampling oscilloscope of rise-time $<4\cdot10^{-10}$ sec) for $4\cdot10^{-10}$ sec/cm sweep time. Triondynamics predicts: (1) The 20 000-ampere current recorded in Oak Ridge, Berkeley, Los Alamos and Moscow[2] rotating plasma experiments can be increased as much as desired using oscilloscopes of rise time sufficiently small. (2) The 10^6 neutrons produced per discharge can be obtained in times as small as desired using switch-times sufficiently small. (3) Results are rather independent of the geometry and the dimensions of the devise used. 4) Every elementary particle is different depending on the conditions in which it is observed, because these conditions modify its meta-coordinates, but all particles have trion configuration. (5) Taking the concept of electrical charge (defined operationally) as the starting point of calculus is more rigorous than taking the two Euclidean axioms, point and line (defined negatively).

[1] J. G. Barredo, Naturwissenschaften 15, 346 (1956), and Bull. Am. Phys. Soc. Ser. II, **4**, 243 (1959).

[2] E. E. Yushmanov, *Plasma Physics*, Vol. IV (to be published).

TUESDAY MORNING AT 9:30

Auditorium, Engineering Society

(T. L. SMITH presiding)

High-Polymer Physics, I

Invited Papers

L1. Determination of Molecular Weights and Distributions of High Polymers by Dilute Solution Measurements. D. MCINTYRE, *National Bureau of Standards.* (40 min.)

L2. Statistical Computation of Polymer Dimensions Using a Monte Carlo Method. F. T. WALL, *University of Illinois.* (30 min.)

Contributed Papers

L3. Theory of Light Scattering by Small Spheroids Subjected to a Velocity Gradient.* A. F. STEVENSON, *Wayne State University.*—A theory of light scattering by ellipsoids whose size is small compared with the wavelength, previously given by the author,[1] has been applied to the case of spheroids subjected to a velocity gradient. The distribution in orientation of the spheroids is assumed to be that given by the theory of Peterlin and Stuart,[2] the numerical calculations of Scheraga, Edsall and Gadd[3] being used.

* This work was supported by the Office of Naval Research.

[1] A. F. Stevenson, J. Appl. Phys. **24**, 1143 (1953).
[2] A. Peterlin and H. A. Stuart, Z. Phys. **112**, 1, 129 (1939).
[3] H. A. Scheraga, J. T. Edsall, and J. O. Gadd, J. Chem. Phys. **19**, 1101 (1951).

L4. Apparatus for Determining the Shape of Macromolecules from Anisotropic Light Scattering and Preliminary Experimental Results.* W. HELLER, R. M. TABIBIAN, T. L. PUGH, M. NAKAGAKI, EIICHI WADA, AND L. PAPAZIAN, *Wayne State University.*—A concentric cylinder apparatus was designed and constructed for determining the size and shape of macromolecules from anisotropic light scattering expected in flowing solutions. Light scattering is studied by means of a lateral opening in the stationary outer cylinder. The angle of observation can be varied up to $\pm 30°$ with respect to the direction of the velocity gradient within either the plane perpendicular to the direction of the primary beam or in the orthogonal plane perpendicular to the direction of flow. The inner cylinder rotating at constant speed ($\pm 1\%$) has a variable diameter so that the shear rate can be varied within wide limits, the maximum for laminary flow being 16 300 sec^{-1}. Observations are being made primarily for the wavelength 5461 a.u. but provision is made for obtaining spectra. In connection with this new method several theories have been developed in this laboratory for determining the numerical dimensions of macromolecules, both rigid and flexible, from the anisotropy of scattering in streaming solutions. In preliminary experiments with solutions of tobacco mosaic virus, one of these theories, that by Okano and Wada, pertinent to rigid rods, was tested successfully.

* This work was supported by the Office of Naval Research.

L5. Non-Newtonian Viscosity of Tobacco Mosaic Virus Solution. KOJI OKANO AND EIICHI WADA,* *Institute of Physical and Chemical Research, Tokyo* (introduced by W. Heller).—The viscosity of tobacco mosaic virus (TMV) solutions is measured at various rates of shear, with a tiltable capillary viscometer at 25°C at shear rates varied from 300 to 1000 sec^{-1}. The curves giving the relative viscosities vs rate of shear G clearly show a limiting slope of value zero as $G \to 0$ and an inflection point at a certain value of G. Both phenomena are in accordance with the expectation from the pertinent molecular theories. The measured reduced viscosity of the 0.409 g/liter solution is 34 cc/g at $G \to 0$. The intrinsic viscosity calculated from Simha's equation is 31 cc/g taking into account the particle size distribution obtained from electron micrographs. The effective rotatory diffusion constant $\bar{D}$ derived from the observed viscosity vs shear rate curve is *ca* 4×10^2 sec^{-1} for $c=0.409$ g/liter. The calculated value of the diffusion constant, D, is 600 sec^{-1} assuming (a) monodispersity, (b) an axial ratio of 18, (c) a length of the major axis of 270 mμ and 25°C. For the actual polydisperse system, the calculated $\bar{D}$ values is 2×10^2 sec^{-1} on using the same particle size distribution mentioned above. It is of interest to note that the $\bar{D}$ value as obtained from the experimental curves of viscosity vs shear rate rapidly decreases with increasing concentration. This suggests a strong mutual interaction between the particles at even very low concentrations.

* Present address: Department of Chemistry, Wayne State University.

L6. An Approximate Isotopic Frequency Rule in the Spectral Analysis of High Polymers. S. KRIMM, *The University of Michigan.*—An isotopic frequency rule has been derived which is valid to a good approximation for individual modes of hydrogen-containing groups within a complex molecule. It is given by $\lambda^i/\lambda = 1-(\Sigma_j \Delta T_j/\rho T)$, where $\lambda = 4\pi^2\nu^2$, $\rho = m^i/m$ (the ratio of the isotopic to the normal mass), T = total kinetic energy associated with the vibration, and $\Sigma_j \Delta T_j$ = differential kinetic energy associated with the substituted atoms. When tested on H_2O and NH_3, the rule reproduces the observed frequency ratios ν/ν^i to within about 0.5%. For the modes of a CH_2 group, this relation predicts the following ratios of ν/ν^i: $\nu_s - 1.379$, $\nu_a - 1.394$, $\delta - 1.349$, $\gamma_w - 1.323$, $\gamma_t - 1.414$, $\gamma_r - 1.379$. It will be shown that, when applied to the analysis of infrared spectra of high polymers, this rule can be of significant help in making assignments. It can also provide information on the separability of group vibrations, and may throw some light on the nature of structural changes between the crystalline and amorphous forms of a polymer chain.

TUESDAY AFTERNOON AT 2:00

Auditorium, Engineering Society

(J. H. GIBBS presiding)

High-Polymer Physics, II

Invited Paper

M1. Application of High-Resolution Nuclear Magnetic Resonance Spectroscopy to the Determination of the Conformation of Polymer Chains. F. A. BONEY, *Minnesota Mining & Manufacturing Company.* (40 min.)

Contributed Papers

M2. Statistical Model for the Thermal Diffusion Effect in Dilute Polymer Solutions.* JOE S. HAM, *A. & M. College of Texas.*—The Brownian motion model for diffusion is extended after Yang[1] to include thermal diffusion effects. By associating two theoretical normal diffusion constants which appear in this theory with the observed polymer diffusion constant and the self-diffusion constant of the solvent, it is possible to obtain a theory of thermal diffusion which depends only upon quantities from experiments at constant temperatures, The deduced dependence of thermal diffusion coefficient upon temperature, solvent, molecular weight, and concentration will be discussed. It will be shown that, in so far as the theory is correct, thermal diffusion is not a promising means to fractionate various molecular weight polymers.

* Supported by Convair, a Division of General Dynamics Corporation.
[1] L. M. Yang, Proc. Roy. Soc. (London) **A198**, 94 (1949).

M3. Experimental Measurements of the Thermal Diffusion Effect.* FRANK C. WHITMORE, *A. & M. College of Texas.*—The thermal diffusion ratio for polystyrene in toluene has been measured for a variety of molecular weights. The measured dependency of the thermal diffusion ratio on the concentration, molecular weight and the average temperature will be presented. From a knowledge of the normal diffusion constants of these same solutions, the thermal diffusion ratio can be computed. A comparison of the experimental data with the theory of Ham[1] will be presented.

* Supported by Convair, a Division of General Dynamics Corporation.
[1] J. S. Ham (preceding abstract).

M4. Diffusivities and Solubilities of Gases in Polymers. J. L. LUNDBERG, M. B. WILK, AND MARILYN J. HUYETT, *Bell Telephone Laboratories.*—Studies of the sorption of gases by polymers have been extended by further investigation of the systems nitrogen-polyethylene and methane-polyethylene and by extending our studies to the system methane-polystyrene. Radial diffusion into a cylinder of liquid polymer is followed by measuring pressure change with time at constant volume and constant temperature. An analog and digital data recording system is used to measure pressure, time, and temperature. Diffusion coefficients and solubilities are estimated from sorption data by fitting a combination of two close approximations to the solution of the diffusion equation for radial diffusion in an infinite cylinder. An iterative method based upon least squares is used on a high speed digital computer. Time dependence of the diffusion coefficient and its effect upon estimates of diffusion coefficients and solubilities from sorption data as well as the statistical interdependence of estimates of diffusion coefficients and solubilities are discussed. The temperature and pressure dependence of diffusivities and solubilities have been determined.

M5. Effect of Crosslinking on the Diffusion of Small Molecules into Elastomers. D. J. BUCKLEY AND M. BERGER, *Esso Research and Engineering Company.*—The diffusion of small molecules into crosslinked elastomers is studied by means of swelling the elastomer in a liquid. An optical system records the complete "time-swell" curve from which diffusion coefficients can be calculated. It is shown that the diffusion of the molecules through the network is dependent in part on the network structure achieved during vulcanization. Diffusion decreases significantly as the molecular weight of the polymer chain between points of juncture decreases. A similar effect in reduction of diffusion coefficient is observed when the "points of juncture" are due to the presence of fillers such as carbon black. This relation between diffusion and the tightness of the network structure is discussed in terms of reinforcement and mechanical properties. The effect of various diffusant molecules on the above relationship is also discussed.

M6. Determination of the Anisotropy of Bond-Polarizability of Liquids Using Flow-Birefringence Measurements. W. PHILIPPOFF, *Esso Research and Engineering Company* (introduced by T. L. Smith).—According to the theories of Raman and Krishman, Peterlin and Stuart, and Kuhn and Grün, flow birefringence can be expressed as a "stress-optical coefficient *C*" which connects the amount of birefringence with the shear stress. It is proportional to the anisotropy of the polarizability of the molecule, a quantity measurable using the Kerr effect or the depolarization of scattered light. A series of *n*-alcohols from C_7 to C_{16} were investigated at different temperatures and the anisotropy for a CH_2 group calculated from the data. It checked well with existing results, proving the soundness of this approach. The increment due to the C=C bond was determined using the undecylic and undecylenic acid and also checked satisfactorily with existing results. This gave the experimental foundation for the calculation of the flexibility parameter "*q*" of polymer molecules.

M7. The Birefringence of Polypropylene Crystals.* D. A. KEEDY, J. POWERS, AND R. S. STEIN, *University of Massachusetts.*—The birefringence of a crystal of polypropylene is calculated in terms of bond polarizability ellipsoids. On the basis of the Natta structure of the crystals, all C−C and C−H bonds are assigned vector coordinates. This permits the ready calculation of distances between any pair of atoms and angles between any pair of bonds. From these, the polarizabilities along the axes of the polypropylene helix and perpendicular to this direction are calculated. From these and the known arrangement of helices in the unit cell, the principal refractive indices of the crystal are calculated. Interactions between bond polarizabilities and between helices in the crystal are neglected. The calculated results depend upon which of the differing reported bond polarizabilities of the C−C bond are used. A birefringence of 0.015 is obtained using Bunn's values

and 0.067 using Denbigh's. Estimated birefringence values of 0.02 to 0.03 are obtained in this laboratory and by Wilchisky, and a value of 0.027 is reported by Kieth. These results indicate that the polarizability of a C−C bond in the polypropylene crystal is greater than that in polyethylene. It is felt that the bond polarizability tensor is dependent on configuration because of internal field.

* Supported in part by a contract with the Office of Naval Research and in part by grants from the National Science Foundation and the Plax Corporation and assistance from the Monsanto Chemical Company.

Business Meeting of the Division of High Polymer Physics

(to be called during the session whenever the Chairman wishes)

TUESDAY AFTERNOON AT 2:15

Auditorium, Institute of Arts

(H. Y. FAN presiding)

DSSP Symposium on Radiation Effects in Solids

MA1. Present Knowledge of Irradiation Damage in Crystals. J. S. KOEHLER, *University of Illinois.* (40 min.)

MA2. Stored-Energy Release below 80°K in Deuteron—Irradiated Copper. T. G. NILAN, *University of Illinois.* (30 min.)

MA3. Mathematical Microscopy of Radiation Effects. G. H. VINEYARD, *Brookhaven National Laboratory.* (30 min.)

MA4. Defects Produced in Silicon by Electron Irradiation. G. D. WATKINS, *General Electric Research Laboratory.* (30 min.)

TUESDAY AFTERNOON AT 2:15

WSU McGregor Memorial

Conference Center Room L

(A. W. OVERHAUSER presiding)

Nuclear Magnetic Resonance

N1. Volume Dependence of the NMR in Ferromagnetic Cobalt.* R. V. JONES AND I. P. KAMINOW,† *Harvard University.*—The NMR frequency of Co^{59} in cubic cobalt metallic powder has been observed as a function of hydrostatic pressure to 6000 kg/cm². At 296°K the pressure shift is found to be quite linear over this range and can be represented as $(\partial \ln\nu/\partial P)_T = 6.01 \pm 0.01 \times 10^{-7}$ (kg/cm²)$^{-1}$. At 195°K the pressure shift is within 3% of this same value. From estimates of the volume compressibility of cubic cobalt the volume dependence of the resonance frequency is given by $\partial \ln\nu/\partial \ln V = -1.19 \pm 0.06$. Marshall[1] has given theoretical estimates of the various contributions to the magnetic field at the cobalt nucleus in hexagonal cobalt. Following Portis and Gossard's[2] adaptation of this model to the case of cubic cobalt and using previous experimental data, where available, we have tried to infer the main source of the volume dependence of the resonance frequency. It is felt that the main contribution arises from a increase in the admixture of 4*s* wave functions into the 3*d* band with decreasing lattice constant.

* Research supported by contract with AFCRC.
† Bell Telephone Laboratories CDTP Fellow.
[1] W. Marshall, Phys. Rev. 110, 1280 (1958).
[2] A. M. Portis and A. C. Gossard, AIEE 1959 Conference on Magnetism and Magnetic Materials, J. Appl. Phys. (to be published).

N2. On Inhomogeneous Broadening of Nuclear Resonance in Magnetic Domain Walls. H. SUHL, *Bell Telephone Laboratories.*—The Co^{59} NMR in cubic cobalt metal reported by Portis and Gossard,[1] was found by them to be inhomogeneously broadened to about 400 oersteds at room temperature. We here report a temperature-dependent mechanism for inhomogeneous broadening contributing some fraction to this total width. The participating nuclei reside in the domain walls.[2] The average thermal deviation of the electronic spin density causing the hyperfine field at the nuclei is shown to vary through the wall. Consequently each nuclear spin sees a slightly different hyperfine field. For a simple model, with demagnetizing neglected, the fractional spread $\Delta H/H$ in hyperfine fields is found to be $\Delta H/H \sim (E_A/kT)^{\frac{1}{2}} \delta M/M$ where $\delta M/M$ is the thermal deviation of M in the bulk sample. This formula assumes $kT \gg E_A$; otherwise the root is replaced by unity. At room temperature, with $\delta M/M = 0.02$[3], ΔH for cubic cobalt is ~40 oersteds. With demagnetizing the problem cannot be solved sufficiently generally,[4] it may be argued that the effect is then enlarged. The zero point effect connected with quantization of this mechanism is found to be negligible ($\Delta H \sim 1$ oersted).

[1] A. C. Gossard and A. M. Portis, Phys. Rev. Letters 3, 164 (1959).
[2] A. M. Portis and A. C. Gossard, Magnetism Conference Proceedings, Detroit, Michigan, 1959, J. Appl. Phys. (to be published).
[3] V. Jaccarino, Bull. Am Phys. Soc. Ser. II, 4, 461 (1959).
[4] L. R. Walker has solved a special case (to be submitted to J. Appl. Phys.).

N3. Nuclear Resonance Saturation in Li^7. R. BLUME AND A. REDFIELD, *IBM, Watson Laboratory.*—We have studied the dispersion signal at 77°K in metallic Li^7 in the vicinity of saturation. By using slow passage and no modulation the data is easily interpreted theoretically.[1] The dispersion narrows markedly and the dispersion derivative increases at the onset of saturation, consistent with previous observations.[1,2]

[1] A. Redfied, Phys. Rev. **98**, 1787 (1955).
[2] D. Holcomb, Phys. Rev. **112**, 1599 (1958).

N4. Knight Shift in Metallic Potassium. W. B. GAGER AND F. J. MILFORD, *Battelle Memorial Institute.*—The K^{39} nuclear magnetic resonance has been observed in metallic potassium and in potassium nitrate and potassium cobalticyanide. The observations were made at room temperature using a Varian V 4200 B wide line NMR spectrometer. Field sweep was used with a constant radio frequency of 1.9745 ± 0.0001 Mc. The metallic sample was prepared by ultrasonically dispersing molten potassium in molten paraffin. In $K_3Co(CN)_6$ the resonance occurred at 9940.5 ± 0.5 gauss, in KNO_3 at 9939.9 ± 0.5 gauss, while in the metal it occurred at 9915.6 ± 0.5 gauss. From this data a Knight shift of $(0.248 \pm 0.005)\%$ is calculated. A theoretical value for the Knight shift of 0.206% is obtained by combining Callaway's perturbation calculation[1] and Pines theoretical spin susceptibility. We have also used the quantum defect method together with Kohn's variational procedure to calculate the Knight shift in potassium. The result, 0.254%, is in excellent agreement with the experimental value and completely consistent with Brooks' results[2] for the other alkali metals.

[1] J. Callaway in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1958), Vol. 7, p. 144.
[2] H. Brooks (unpublished, quoted in Callaway, reference 1).

N5. Nuclear Spin Relaxation in Superconducting Al. Y. MASUDA, *Columbia University,* AND A. REDFIELD, *IBM Watson Laboratory.*—A systematic error has been found in the previously reported[1] measurements of relaxation time. The measurements have been repeated and extended to 0.36°K, using the same sample. The relaxation time is about 20% greater than previously reported, corresponding to the same gap of $3.25\ kT_c$ and a somewhat smaller value of the parameter[2] r (about $r=10$ instead of 15). According to the interpretation of reference 1, r^{-1} is a measure of the anisotropy of the energy gap.

[1] A. Redfield, Phys. Rev. Letters **3**, 85 (1959).
[2] L. C. Hebel, Phys. Rev. **116**, 79 (1959).

N6. Nuclear Quadrupole Interactions in Dilute Copper Alloys. T. J. ROWLAND, *Union Carbide Metals Research Laboratories.*—The major effects of the addition to copper of a wide variety of B subgroup elements on the nuclear magnetic resonance absorption of copper will be reported. The dependence of the resonance amplitude upon solute species and concentration in these primary substitutional solid solutions will be stressed. The amplitude changes are the result of interactions between the nuclear electric quadrupole moments of copper nuclei and the electric gradients generated by the solute atoms. The experimental data show that the gradient surrounding a solute atom is proportional to its excess charge Z' (valence difference between solute and copper), and is practically independent of its size (using various current concepts), except for $Z'=0$. Furthermore, these gradients are shown to diminish only as $1/r^3$. This behavior is in essential agreement with ideas recently expressed by Friedel and with the theory of Kohn and Vosko.[1] Using calculated gradients[1] the complete absorption spectra have been computed for several alloys and found to be in good agreement with experiment.

[1] W. Kohn and S. H. Vosko (following abstract).

N7. Theory of Nuclear Resonance Intensity in Dilute Alloys.* W. KOHN AND S. H. VOSKO, *Carnegie Institute of Technology.*—Experiments of Bloembergen and Rowland[1] have shown that the intensity of the nuclear resonance signal in metallic Cu decreases rapidly when small quantities of other elements are alloyed with it. These results imply that each solute atom produces significant electric field gradients in an extended region, sometimes affecting as many as 85 neighboring Cu nuclei. We suggest that these field gradients arise largely from spatial oscillations of the conduction electron density produced by each solute atom in its vicinity.[2] These oscillations have the form $\cos(2k_F r+\varphi)/r^3$ where k_F is the Fermi momentum and φ is a phase. An approximate calculation of the magnitudes of the field gradients agrees with experiment within a factor of about 1.5.

* Research supported by an ONR contract.
[1] N. Bloembergen and T. J. Rowland, Acta Met. **1**, 731 (1953); T. J. Rowland (preceding abstract).
[2] J. Friedel, Nuovo cimento, Suppl. **2**, 287 (1958).

N8. Nuclear Relaxation by Impurities in Metals. L. C. HEBEL, *Bell Telephone Laboratories.*—Sharpness of the Fermi surface in a metal results in periodic variations in electric charge[1] or spin[2] density near an impurity atom. Consequently, the electric field at a distance R is $E(R) \cong [\sin(2k_0R)]/6k_0R^3$, $k_0R \gg 1$, where k_0 is the Fermi wavevector. Thus, the long range, periodic gradient makes nuclear quadrupole interactions with impurities in metals much more important than is indicated by previous calculations using exponential screening in a Debye length. We have studied nuclear spin relaxation in aluminum at zero external magnetic field using both positive and negative temperature spin distributions. Our results and unexplained effects reported by Hebel and Slichter,[3] and Anderson and Redfield[4] are explained by adding the long range impurity effects mentioned above to the previous theory.

[1] E. Daniel, J. phys. radium, **20**, 769 (1959).
[2] M. A. Rudermann and C. Kittel, Phys. Rev. **96**, 99 (1954).
[3] L. C. Hebel and C. P. Slichter, Phys. Rev. **113**, 1504 (1959).
[4] A. Anderson and A. G. Redfield, Phys. Rev. (to be published).

N9. Nuclear Resonance Saturation Effects in NaCl and CaF_2.* WALTER I. GOLDBURG, *The Pennsylvania State University.*—It is found that the nuclear magnetization M_z measured as a function of frequency ω and amplitude $2H_1$ of the saturating rf field, is not given by the usual expression $M_z \sim [1+\gamma H_1{}^2 g(\omega) T_1/2]^{-1}$ for the Na^{23} spin system in NaCl if $H_1 \gtrsim 1.5 \times 10^{-3} \Delta\nu_{Na}$. Here γ is the gyromagnetic ratio, $g(\omega)$ is the normalized line shape, and $\Delta\nu$ is the full absorption line width at half maximum. The above expression is in agreement with the observed $M_z(\omega, H_1)$ for the F^{19} spins in CaF_2 for H_1 up to 0.135 gauss $\simeq 3 \times 10^{-3} \Delta\nu_F$. Holcomb,[1] however, has measured the absorption, $\chi''(\omega)$, in CaF_2 and observes the onset of saturation effects at higher H_1 than was available in these experiments. The technique used here was to measure M_z by pulse techniques immediately after $H_1(\omega)$ was turned off. The saturating field remained on for a time much greater than the spin-lattice relaxation time, T_1. In the samples used, $T_1(Na) = 14$ sec and $T_1(F) \simeq 13$ sec at room temperature and 77°K, the temperatures at which the respective measurements were made.

* Supported in part by the National Science Foundation. Most of the work was done at Carnegie Institute of Technology.
[1] D. F. Holcomb, Phys. Rev. **112**, 1599 (1959).

N10. Nuclear Spin Relaxation in Water. S. MEIBOOM, *Bell Telephone Laboratories.*—The observation that the transverse relaxation time T_2 of protons in water is shorter than the longitudinal relaxation time T_1 has been reported previously.[1] In variance with the former explanation it has now been found

that this is due to the spin-spin interaction of the protons with O^{17}. Measurements on water enriched in O^{17} show that the effect is proportional to O^{17} concentration. Also, the T_2 of the O^{17} resonance shows a behavior similar to that of the protons. The transverse relaxation was measured by a method due to Solomon.[2] By measuring the relaxation time as function of applied H_1 the spin-spin interaction and the rate of proton transfer can be found separately. Theoretical equations for interpreting such measurements will be presented, as well as values for the rate constants of proton transfer in water.

[1] Meiboom, Lux, and Gill, J. Chem. Phys. **27**, 1411 (1957).
[2] I. Solomon, Compt. rend. **248**, 92 (1959).

TUESDAY AFTERNOON AT 2:15

WSU McGregor Memorial

Conference Center Room B

(E. BURSTEIN presiding)

Magneto-Optical Properties and Cyclotron Resonance

NA1. Cyclotron Resonance in ZnSb and CdSb. MIREK J. STEVENSON, *IBM, Poughkeepsie.*—Cyclotron resonance absorption was observed in single crystals of the II–V intermetallic semiconductors ZnSb and CdSb prepared by V. J. Lyons of our laboratory. Several p-type ZnSb crystals were pulled in a sealed tube from a melt of zinc and antimony of 99.999+% purity. A single cyclotron resonance absorption line was observed at magnetic fields corresponding to an effective mass $m^*=0.15m_e$. The effective mass was almost isotropic in the three crystal planes with small anisotropy observed in the planes containing the b axis. The resonance can be interpreted in terms of an almost spherical energy surface for either the conduction or the valence band, depending on whether the resonance is associated with electrons or holes, respectively. The line width of the resonance revealed a very critical dependence on the crystal growth pattern, with the best resonance lines given by the relaxation time $\tau=1.2\times10^{-11}$ sec. A single cyclotron resonance absorption line was also observed in p-type CdSb pulled from a melt of 99.999+% pure triply distilled cadmium and 99.999+% pure antimony. The resonance corresponded to an effective mass $m^*=0.15m_e$, the same value as for ZnSb. The resonance was almost isotropic as would be the case for a spherical energy surface. Very slight anisotropy was observed in planes containing the b crystal direction. The relaxation time τ was 1.5×10^{-11} sec for the best resonances obtained.

NA2. Maser Approach to Emission from Negative Masses. R. C. DUNCAN, JR., AND B. ROSENBLUM, *RCA Laboratories.*—The experiments of Dousmanis *et al.*[1] have shown a net emission in cyclotron resonance from light-excited, negative mass holes in germanium. A simple and instructive semiclassical model for the Landau level system of these carriers will be presented. Coherent emission from these carriers must, as in a maser, be a result of sufficient inversion of the population in this level system. The question of how such an inversion may come about is treated by considering in a general way, the generation, recombination, and scattering of the light-excited carriers. The spontaneous emission of acoustical phonons appears to be the most likely process for producing an inversion. It will be pointed out that certain factors tending to prevent a significant inversion in most Landau level systems are absent in this case. Perhaps the most important of these is that the carriers at very low energies do not contribute to the negative mass resonance.

[1] G. C. Dousmanis, R. C. Duncan, Jr., J. J. Thomas, and R. C. Williams, Phys. Rev. Letters 1, 404 (1958).

NA3. Negative Effective Mass Cyclotron Resonance Experiments.* R. N. DEXTER, D. HENSLER, E. HOLLAR, AND M. HALLORAN, *University of Wisconsin.*—Experiments at liquid helium temperatures have been performed on germanium and silicon at 24 Kmc in unsuccessful attempts to confirm the work of Dousmanis[1] which indicated emission due to negative effective mass heavy holes in germanium. No positive evidence of emission in several p-type samples was found using linearly or circularly polarized microwaves and wide ranges of microwave power and light intensity and temperature variation between 1.3°K and 5°K. There was extra absorption near breakdown which might correspond to absorption by negative mass carriers. For a [100]-directed magnetic field, the third-harmonic resonance of the heavy holes in germanium always absorbed energy resonantly under circular polarization conditions appropriate for *electron* resonance; the fifth-harmonic resonance of the heavy holes behaved like the light and heavy holes however. The identification of the third-harmonic resonance as a hole resonance was confirmed by observing the effects of impact-ionization breakdown and carrier density augmentation as well as by resonance-field measurements.

* Supported in part by the Wright Air Development Center.
[1] G. C. Dousmanis, R. C. Duncan, Jr., J. J. Thomas, and R. C. Williams, Phys. Rev. Letters 1, 404 (1958).

NA4. Magnetoplasma Reflection in n-Type InSb and n-type HgSe. GEORGE B. WRIGHT AND BENJAMIN LAX, *Lincoln Laboratory,** *MIT.*—We have observed the splitting, in a magnetic field, of the plasma reflection edge due to conduction electron susceptibility of InSb and HgSe.[1] Analysis of the splitting gives a direct determination of the electron effective mass, independent of the relaxation time τ, and of the carrier concentration N. If the effective conductivity is expanded in powers of H, the tensor coefficients for the zero, linear, and quadratic terms are found to be the dispersive analogs of the cunductivity, Hall coefficient, and magnetoresistance coefficient. The zero field term gives the ordinary plasma edge. The splitting reported here was dominated by the linear term. A typical value of the electron effective mass in HgSe was $m^*/m=0.045\pm0.005$ for a concentration $N=2.5\times10$ cm^{-3}. Data will be presented on the change of effective mass with carrier concentration.

* Operated by MIT with support of U. S. Army, Navy, and Air Force.
[1] B. Lax and G. B. Wright, Phys. Rev. Letters 4, 16 (1960).

NA5. Magneto-Optical Effect in Strained and Unstrained Germanium.* DAVID F. EDWARDS AND VITO J. LAZAZZERA, *The University of Michigan, Willow Run Laboratories.*—Measurements have been made of the direct transition magneto-optical effect in strained and unstrained specimen of intrinsic germanium at 77°K. Magnetic fields up to 24 kilogauss and resolving powers of about 13 000 were used. For the unstrained

specimen the zero magnetic field exciton was measured to have an energy of $E_s=0.88174$ ev with no second absorption at a slightly higher energy being observed. This is in agreement with the data of Macfarlane *et al.* Extrapolation of the Landau absorptions to zero magnetic field gives the value of the direct transition energy gap as $E_g=0.88054$ ev. For the strained samples the values of E_g and E_s depend on the magnitude of the strain with the largest value of $E_s=0.8890$ ev being measured. In all cases measured the strains were compressional. The strained and unstrained samples had several common features. With a magnetic field the two lowest levels behaved nonlinearly with B. The exciton energy was greater than the gap energy. No assymetries with respect to crystallographic direction or polarization were observed in either the exciton or Landau absorptions. In both cases the lower limit of the exciton lifetime is about 6×10^{-13} sec as estimated from the half-width of the zero magnetic field exciton.

* This work supported by Project MICHIGAN (administered by the U. S. Army Signal Corps).

NA6. Magneto-Optical Effects in Cadmium Sulfide.* R. G. WHEELER AND J. O. DIMMOCK, *Yale University.*—Additional Zeeman structure[1] of the exciton lines and possible magnetoabsorption structure has been observed in cadmium sulfide. The measurements were made at 1.8°K on crystals approximately 0.7 μ thick, thus extending the absorption spectrum to 4790 A. Plane polarized light, $E\|C$ axis, was used for magnetic fields up to 19.7 kilogauss with orientations $H\perp C$ and $H\|C$. Three additional lines at 4814, 4813, and 4806 A were observed to split in the field. The splittings are as follows: 4814 A, two components $g_\perp=1.8$, one component $g_\|<0.5$; 4813 A two components $g_\perp=2.6$, four components $g_\|=1.7$; 4806 six components $g_\perp=4.2$, one component $g_\|<2.0$. These lines also exhibited substantial diamagnetic shifts to higher energy in the magnetic field. Also there was observed at high magnetic fields in the region of 4805 to 4790 A, a series of absorption lines whose energy increased linearly with field. These lines were only observable in the $H\|C$ orientation since, in the $H\perp C$ orientation, the six Zeeman components of the 4806 A exciton line with superposed diamagnetic shift masks the observation of magnetoabsorption lines. A preliminary identification and interpretation of the magnetoabsorption indicates a band edge at approximately 20805 cm^{-1} and a reduced effective mass of $0.068\pm0.004m_e$.

* Supported by the U. S. Air Force Office of Scientific Research.
[1] R. G. Wheeler and J. O. Dimmock, Phys. Rev. Letters 3, 372 (1959).

NA7. Excitation of Si and Ge Donor Levels in Magnetic Fields. WILLIAM FRANK. *United States Naval Ordnance Laboratory.**—A calculation is made of the P wave like levels of donor electrons in Si and Ge in magnetic fields of 10 to 50 kilogauss oriented along the [100] axis. A variational calculation is based on the effective mass formalism. The trial wave function is chosen of the form

$$\psi^m = Nr\,Y_1{}^m(\theta,\phi)\,\exp-[A(x^2+y^2)+Cz^2]^\nu,$$

where A, C, and ν are parameters, and the z axis is along the [100] direction. The adequacy of this form will be discussed. The results for Si in this field range are substantially the same as those of perturbation theory, while for Ge the fields are effectively strong. Results will be shown and discussed.

* Work done in part at Lincoln Laboratory, MIT.

NA8. Theory of Magneto-Optic Absorption of Impurity States and Excitons.* R. E. HOWARD AND H. HASEGAWA, *Carnegie Institute of Technology.*—Some features of the high field magnetoabsorption spectrum are discussed in terms of the methods developed by Yafet, Keyes, and Adams[1] and Wallis and Bowlden.[2] In particular, it is shown that for $\mathbf{E}\perp\mathbf{H}$ and for $\mathbf{H}\to\infty$ only transitions to a single bound state are allowed. The absence of a photoionization peak in measurements on InSb[3] is thus explained. It is suggested that the magnetoabsorption spectrum of As in Ge, measured by Boyle,[4] may be understood in terms of transitions from the ground state to bound excited states, rather than to so-called Landau levels. Applications to exciton absorption in a magnetic field are discussed.

* Research supported by an ONR contract.
[1] Y. Yafet, R. W. Keyes, and E. N. Adams, J. Phys. Chem. Solids 1, 137 (1956).
[2] R. F. Wallis and H. J. Bowlden, J. Phys. Chem. Solids 7, 78 (1958).
[3] W. S. Boyle and A. D. Brailsford, Phys. Rev. 107, 903 (1957).
[4] W. S. Boyle, J. Phys. Chem. Solids 8, 321 (1959).

Invited Paper

NA9. Magnetomechanical Determination of g-Factors. G. C. SCOTT, *General Motors Corporation.* (30 min.)

TUESDAY AFTERNOON AT 2:15

Auditorium, Rackham Memorial

(P. W. ANDERSON presiding)

Theory

O1. Irreversibility and the Derivation of the Transport Equation. J. R. SCHRIEFFER, *University of Illinois,* AND M. H. COHEN, *University of Chicago.*—In deriving the transport equation for an isolated system, one might suppose the system to be in thermal equilibrium in the remote past and that an electric field E is turned on adiabatically.[1] Alternatively, one could turn off E from a finite value and require the system to be finally in thermal equilibrium.[2] We have shown rigorously that the former situation leads to the physically correct result, whereas the latter leads to a current in opposition to E. The two solutions differ by a solution of the homogeneous equation ($E=0$) for the full density matrix, ρ. A macroscopic system does not return to its initial state even if E is turned on and off adiabatically. Real transitions of infinitesimal frequency occur and produce persistent off-diagonal elements of ρ even to first order in E. This inherent dynamical irreversibility is a result of the densely packed energy levels of a macroscopic system. Thus, macroscopic irreversibility follows directly from the time reversal invariant equation for ρ without assumptions of randomness of processes involved and boundary conditions are to be chosen consistent with the physical problem involved.

[1] W. Kohn and J. M. Luttinger, Phys. Rev. 108, 590 (1957).
[2] E. N. Adams, Westinghouse Research Laboratory Scientific Paper 6-43001-1-P1.

O2. Response of the Electron Gas to an External Perturbation. M. H. COHEN, *University of Chicago*, AND H. EHRENREICH, *General Electric Research Laboratory*.—The self-consistent Liouville equation for the one-particle density matrix of the electron gas is susceptible to a normal-mode analysis which generalizes that of Brout and Sawada to finite temperatures. It is found that no collective (plasma) modes exist at finite temperatures. The normal mode analysis provides a means of deriving the response of the electron gas to an external perturbation without resort to an ansatz concerning the time and position dependence of the density matrix. There are two contributions to the response, (1) from the collective and (2) from the individual particle modes; (1) is cancelled precisely by a term in (2). The term in (2) remaining after this cancellation leads to the usual result: the total self-consistent potential is the just external potential divided by a frequency and wave number dependent dielectric constant. The ansatz procedure is thus justified, and familiar results, e.g., screening calculations, are thus given a sounder foundation.

O3. Many-Body Treatment of Electromagnetic Response Functions. R. D. PUFF AND G. W. PRATT, JR., *Lincoln Laboratory,* MIT*.—It is well known that the interaction between a test charge and a charge or current density is altered by the presence of a medium. This alteration is described classically by the dielectric constant ϵ and the magnetic permeability μ. Quantum mechanically, generalized response functions analogous to ϵ and μ can be described readily with the aid of the thermodynamic Green's function formalism recently developed by Martin and Schwinger. These response functions relate the applied external current to the effective potential A_{eff} felt by a test charge. One must distinguish carefully between a real charge in the medium and a test charge, since the latter is both statistically and dynamically uncorrelated with the particles of the medium. The generalized permeability satisfies an equation similar to the integral equation, discussed by various authors, which determined ϵ^{-1}. Successive correlative approximations based on the multiparticle Green's function approach can be applied to these expressions. In addition, a Schrödinger-like one-particle equation is obtained for an uncorrelated charge in the presence of an externally applied electromagnetic field. This provides the basis for an effective mass approximation which includes many body effects on the response of a system to the applied electromagnetic field.

* Operated by MIT with support of the U. S. Army, Navy, and Air Force.

O4. Renormalization of Mass and Charge of Electrons and Holes in Semiconductors.* H. HAKEN,† *Cornell University and General Electric Research Laboratory*, AND F. ENGLERT†, *Cornell University* (introduced by G. Dresselhaus).—Mass and charge of an electron or a hole moving in a periodic potential are altered by its interaction with lattice vibrations and valence electrons. General expressions for the corresponding renormalization constants are derived by means of Feynman's path integral and disentangling techniques. The results are valid for all coupling constants in case of interaction with boson fields. It is shown that, if particles are far apart from each other and move slowly, a weak coupling theory gives the correct result, if renormalized masses and wave functions are used.

* Supported in part by the Office of Naval Research.
† On leave of absence from University of Erlangen, Germany.
‡ On leave of absence from Université Libre de Bruxelles, Belgium.

O5. Dielectric Formulation of Quantum Statistics of Interacting Particles.* F. ENGLERT AND R. BROUT, *Cornell University*.—Formal relations are given which express the free energy in terms of the "dielectric constant" which in turn expresses the response of the system to an external perturbation. Further, the connection with the two-particle Green's functions in temperature space is presented. A general perturbation expansion for free energy and general admittance tensors are established. The application of these results to the problem of the electron correlation at finite temperature in the random phase approximation is indicated.

* Supported in part by the Office of Naval Research.

O6. Existence of Kramers-Kronig Relations for the Magneto-Conductivity Tensor. HAROLD N. SPECTOR,* *University of Chicago* (introduced by M. H. Cohen).—McClure has derived Kramers-Kronig relations between the components of the magnetoconductivity tensor by assuming a relaxation time which is constant along the carrier orbits and a special symmetry for the band structure.[1,2] We have found that the Kramers-Kronig relations no longer hold once we abandon the constancy of the relaxation time on the orbit. However, the validity of the dispersion relations does not require any special symmetry of the energy surfaces or the orientation of the magnetic field, but only that the relaxation time be constant along the carrier orbit.

[1] J. McClure, Phys. Rev. **101**, 1642 (1956).
[2] J. McClure, Phys. Rev. **112**, 715 (1958).

O7. Noise in Driven Quantum-Mechanical Systems. MELVIN LAX, *Bell Telephone Laboratories*.—A previous treatment[1] of fluctuations in Markoffian, classical, stationary driven systems is extended to include quantum-mechanical, nonstationary, aged systems that interact weakly with a reservoir. The second quantized system density matrix operators $\sigma_{ji}=a_i^\dagger a_j$ are chosen to be the set of Markoffian random variables which predict their own future. The usual density matrix, $\sigma_{ji}=\langle\sigma_{ji}\rangle$, has fluctuations $\Delta\sigma_{ji}=\sigma_{ji}-\sigma_{ji}$ that rigorously obey $\langle\Delta\sigma_{qp}\Delta\sigma_{lk}\rangle=\delta_{qk}\sigma_{lp}-\sigma_{qp}\sigma_{lk}$. The time evolution of the system can also be written rigorously in the form $\sigma_{ji}(t)=\Sigma O_{qp}{}^{ji}(t,t')\sigma_{qp}(t')$ where the decay functions $O(t,t')$ in practice are calculated from an approximate phenomenological theory. The noise in a system variable $I(t)$ can be expressed in terms of the autocorrelation $\langle I(t)I(t')\rangle$. If the density matrix of system+reservoir can be factored approximately à la Bloch-Wangsness, then

$$\langle I(t)I(t')\rangle\approx\Sigma I_{ij}I_{kl}O_{kp}{}^{ji}(t,t')\sigma_{lp}(t')$$

expresses the autocorrelation in terms of the phenomenological decay functions.

[1] M. Lax, Revs. Modern Phys. **32**, 25 (1960).

O8. Proposal of a Principle for Irreversible Statistical Mechanics of Markoffian Systems. RYOICHI KIKUCHI, *Hughes Aircraft Company*.—A principle is proposed which governs irreversible changes of state of Markoffian systems and is good even when the deviations from equilibrium are large. A *path*, which means a change of state for a short time interval τ, is described by a set of *path parameters* $\{P\}$. For an isothermal change, the *path probability* $\mathcal{G}$ of occurrence of a path is made up of three parts. $k\ln\mathcal{G}$ is a sum of the *kinetic probability* term $\mathcal{P}$, the *path entropy* of the system $\mathcal{S}^{(s)}$, and that of the heat bath $\mathcal{S}^{(b)}$: $\mathcal{P}$ depends on the mechanical transition probabilities; $\exp(\mathcal{S}^{(s)}/k)$ is the number of different paths specified by the same parameters $\{P\}$; and $\mathcal{S}^{(b)}$ is the decrease in energy of the system during τ divided by twice the absolute temperature of the heat bath. The most probable path can be obtained by maximizing $\mathcal{G}(t;t+\tau)$ with respect to $\{P\}$ while keeping the properties at t fixed. For a simple noncooperative system, the most probable path thus derived satisfies the kinetic equation based on an intuitive argument, and thus satisfies all the known rules of irreversible thermodynamics. An application to irreversible relaxation of order in an order-disorder system will be discussed.

O9. Propagation of Temperature Waves in Metals. JOSEPH N. FRITZ,* *Cornell University*.—The Boltzmann transport equation is solved in the limit of long electron mean free path.

No effect comparable to the anomalous skin effect for the propagation of electromagnetic waves is found. Departures from the normal diffusion equation are discussed.

* Eastman Kodak Predoctoral Fellow.

O10. Screened Impurity Potentials in Metals. E. C. McIrvine,* *General Atomic.*—Some observations will be made on the real-space potential corresponding to a Fermi-Thomas treatment[1] of screening by conduction electrons. A "plasma screening" parameter $q_p=(m\omega_p/\hbar)^{\frac{1}{2}}$ governs screening when $\zeta\ll\hbar\omega_p$, where ζ is the Fermi energy and ω_p is the plasma frequency. For $\hbar\omega_p<2\zeta$, the Fermi-Thomas solution is, to first order, the exponentially screened Mott potential with parameter $q=(6\pi ne^2/\zeta)^{\frac{1}{2}}$. For $\hbar\omega_p>4\zeta$, a different expansion yields, to lowest order, a potential having oscillatory nature and screening characterized by q_p:

$$U(r)=-(Ze^2/r)\cos(q_pr)\exp(-q_pr).$$

For copper, the calculated plasma frequency gives $\hbar\omega_p=1.9\zeta$; characteristic energy losses would indicate $\hbar\omega_p=4.2\zeta$. Clearly, neither Mott nor plasma screening applies rigorously. The actual potential, the general solution of the Fermi-Thomas problem, will contain oscillatory behavior dominated by exponential screening with a parameter given roughly by the smaller of the two screening parameters q and q_p.

* Now at Scientific Laboratory, Ford Motor Company, Dearborn, Michigan.
[1] N. Takimoto, J. Phys. Soc. Japan **14**, 1142 (1959). Also A. D. Brailsford (private communication).

O11. Zero-Point Energy of an Electron Crystal. R. C. Horsfall and A. A. Maradudin, *University of Maryland.*—At very low densities an electron gas in a compensating uniform background of positive charge crystallizes into a body-centered cubic lattice for which the correlation energy is known.[1] At higher densities the first correction to this result arises from the zero-point energy of the electrons. Kohn's sum rule[2] leads to an upper bound of $E_0/N<\frac{3}{4}(0.57735)\hbar\omega_p$ for the zero-point energy per electron, where ω_p is the classical plasma frequency. Alternatively, the zero-point energy can be expanded in terms of the even moments of the frequency spectrum.[3] Since all terms in this expansion past the first one are negative, breaking off the expansion at any term gives an upper bound to the energy. With only the first four nonvanishing moments we obtain an upper bound of $E_0/N<\frac{3}{4}(0.573)\hbar\omega_p$. A better estimate can be obtained using the known asymptotic behavior of the higher moments which allows the complete expansion to be summed. This procedure leads to the estimate $E_0/N\approx\frac{3}{4}(0.533)\hbar\omega_p$.

[1] K. Fuchs, Proc. Roy. Soc. (London) **A151**, 585 (1935).
[2] R. Brout, Phys. Rev. **113**, 43 (1959).
[3] C. Domb, A. A. Maradudin, E. W. Montroll, and G. H. Weiss, Phys. Rev. **115**, 24 (1959).

O12. Transport with Space Charge of a Pulse of Current Carriers Injected in a Semiconductor. W. van Roosbroeck, *Bell Telephone Laboratories.*—In many experiments, in semiconductor detectors for energetic charged nuclear particles, and in other devices, material of high resistivity is involved and approximate local electrical neutrality does not obtain. From a general formulation with space charge, exact solutions have been obtained in closed form for the linear small-signal case of one-dimensional drift with recombination of an injected pulse. These entail a condition for unperturbed applied field, E_0. For large times and not too strongly extrinsic material, the electron and hole distributions are similar Gaussian distributions displaced by the "polarization distance," x_P, the distance electrons and holes drift apart in the dielectric relaxation time, $\tau_d=\epsilon/4\pi\sigma_0$. These distributions drift at the ambipolar velocity and spread, exhibiting an apparent diffusion. A "pseudo-diffusivity," D_v, is defined. Substantially proportional to $\tau_dE_0^3/\sigma_0^2$, for intrinsic material it equals the ambipolar diffusivity if E_0 equals kT/e divided by the Debye length $(kT\epsilon/8\pi n_ie^2)^{\frac{1}{2}}$, or 10 v/cm for silicon at 300°K. In sufficiently strongly extrinsic material, the minority carriers drift in a delta pulse which leads the majority carriers distributed in an exponential tail of characteristic length x_P, which may be quite large. The results have been extended for arbitrary velocity functions and to include nonlinear effects with high-level injection.

O13. High Fields in Shadow Regions on Photoconductors.* S. Machlup and J. D. Nixon, *Western Reserve University.*—A narrow shadow region separating the anode and cathode portions of a homogeneous high-resistance photoconductor (CdS) may show some of the characteristics of a p-n junction. The anode-cathode asymmetry[1] can be ascribed to the high field in the shadow region and to the large mobility ratio b (electron:hole mobility). When the shadow is rapidly moved a short distance toward the anode the persistence, for a time $\rho\kappa$, of the field in the newly illuminated region may cause the mobile electrons within it to be swept into the shadow region, lowering its resistance. The characteristic (maximum) width d of the shadow for this effect is $(V\mu\tau)^{\frac{1}{2}}$: An electron of mobility μ travels a distance d in its lifetime τ in a field V/d. The minimum widths is the diffusion length $(kT\mu\tau/e)^{\frac{1}{2}}$. Trapping of electrons by surface states will reduce $\mu\tau$, so that it is expected that the conductance anomaly at the shadow may be affected by capacitively applied fields, nonpenetrating background radiation,[2] or surface treatment.

* Supported by the U. S. Atomic Energy Commission and the Office of Ordnance Research.
[1] W. Thielemann, Z. Naturforsch. **12a**, 1023 (1957); **14a**, 92 (1959).
[2] C. R. Finfgeld, G. O. Fritz, and J. D. Nixon (preceding abstract).

Tuesday Afternoon at 2:15

WSU Community Arts Auditorium

(D. Lazarus presiding)

Diffusion, Mostly Noble Metals

OA1. Diffusion in a Chemical Concentration Gradient. John R. Manning, *National Bureau of Standards.*—In chemical interdiffusion experiments, a Kirkendall shift will occur if there is a net flow of atoms past the markers. Such a flow can be caused by a flow of either vacancies or interstitials. A flow of interstitials by a direct interstitial mechanism will not affect the process further. However, either a flow of interstitials by an interstitialcy mechanism or a flow of vacancies will enhance the already existing atom flux, since the flow will tend to make the imperfections approach an atom more often from one side than another. This enhancement will contribute to both the diagonal *and* cross terms in the Onsager formulation of the diffusion equations. Because of this enhancement, the Kirkendall shift and, to a lesser extent, the

chemical interdiffusion coefficients will be larger than predicted by Darken's equations. In a binary alloy, the Kirkendall shift will be larger by a factor $(f_1 f_2)^{-1}$, where f_1 and f_2 are the correlation factors for the two constituents. The factor $(f_1 f_2)^{-1}$ will usually lie between 1.4 and 2.5. Data in the literature for α-brass indicate that an enhancement actually does occur. Thus, the direct interstitial mechanism seems unlikely in this alloy.

OA2. Interstitials in a Face-Centered Cubic Lattice.* ROBERT A. JOHNSON, G. H. GOEDECKE, E. BROWN, AND H. B. HUNTINGTON, *Rensselaer Polytechnic Institute.*—The atomic configuration and energy for an interstitial in a face-centered cubic lattice have been investigated. In a region near the interstitial, a Born-Mayer repulsive potential, $0.053 \times \exp[13.9(r_0-r)/r_0]$ in ev (values applicable to copper), is assumed to act between nearest neighbors. Remaining atoms are treated elastically. Two symmetry configurations are considered: cubic symmetry for a "body-center" interstitial and tetragonal symmetry for an atom pair symmetrically separated in the 001 direction about a normal site. The relaxed configurations are found by an iterative process of minimizing the resultant force on each atom in the near region and on elastic parameters in the elastic region. By energy calculations which neglect changes in electron energy due to redistribution of electrons, the tetragonal symmetry is found to be more stable than the cubic symmetry by 0.08 ev. The neglected contributions should favor stability of the cubic symmetry. Perturbations to the configurations due to the presence of vacancies, and resultant annealing processes, will be discussed and compared with radiation damage experiments.[1]

* Supported by the U. S. Atomic Energy Commission.
[1] J. W. Corbett, R. B. Smith, and R. M. Walker, Phys. Rev. **114**, 1452 (1959).

OA3. Spectrum of Low-Temperature Annealing Processes in Compressed Copper Crystals.* JAMES H. BREDT AND J. S. KOEHLER, *University of Illinois.*—Single crystals of 99.998% pure copper were compressed by a nearly uniaxial stress at 78°K, and measurements of their electrical resistance as a function of time were made at constant temperatures between 78°K and 330°K. The measurements of the potential drop across the specimen had enough sensitivity and precision to measure changes amounting to one unit in the fifth significant figure and the size of the potential ranged from 130 to 760 μv. The specimen temperature was measured with a precision approaching ± 0.001°K, so that the precision of the original potential measurements was preserved in the values of the specimen resistance after they were corrected for small temperature variations which occurred during the anneals. Annealing was continuous in the specimens over the whole temperature range, and in some time intervals the resistance was actually observed to increase. The increases were not confined to unique temperature ranges, but were interspersed rather irregularly among the intervals in which the resistance decreased. Analysis of the data indicates that the annealing involves a very complex spectrum of processes whose activation energies were continuously distributed over an interval at least as wide as 0.6 ev and reached energies at least as high as 0.8 ev.

* Research supported in part by the Office of Naval Research.

OA4. Mass Dependence of Diffusion of Iron in Silver and Copper.* J. G. MULLEN AND D. LAZARUS, *University of Illinois.*—The relative rates of diffusion of iron 55 and 59 in silver and copper have been measured by tracer sectioning techniques. Since the isotopes differ by only seven percent in mass, extreme precision is required in counting. However, as the two iron isotopes have completely different decay schemes, accurate differential counting can be performed, using Be and Au absorbers, after a radiochemical separation of the tracer from the host material. The temperature dependence of the effect will be examined. The connection of the data to the Bardeen-Herring correlation factor will be discussed.

* Supported in part by the U. S. Atomic Energy Commission.

OA5. Measurements of Equilibrium Vacancy Concentrations in Silver.* R. O. SIMMONS AND R. W. BALLUFFI, *University of Illinois.*—Relative changes in macroscopic length, $\Delta L/L$, and x-ray lattice parameter, $\Delta a/a$, of a 99.999% silver bar have been measured from 14 to 956°C, using a rigid parallel pair of filar micrometer microscopes and a rotating-single-crystal x-ray method. The expansions agree within experimental precision (about $1:10^5$) at the lower temperatures. At the higher temperatures ($\Delta L/L - \Delta a/a$) progressively increases, showing that atomic sites are added, corresponding to the thermal generation of vacancy-type defects. The concentration of added sites, $\Delta N/N = 3(\Delta L/L - \Delta a/a)$, at the melting point (obtained by a 4-degree extrapolation) is $1.7 \pm 0.5 \times 10^{-4}$. This value is only 1/5.5 of the corresponding value found for aluminum by the same technique.[1] More than 95% of these extra sites are present as single vacancies if the divacancy binding energy is less than 0.3 ev. For an entropy of formation of $(1.5 \pm 0.5)k$ an energy of vacancy formation of 1.08 ± 0.09 ev is obtained. This formation energy is slightly larger than half the activation energy for self-diffusion, as similar measurements have shown for aluminum[1] and lead, and as quenching experiments have indicated for gold.

* This work was supported by the U. S. Atomic Energy Commission.
[1] R. O. Simmons and R. W. Balluffi, Phys. Rev. (to be published).

OA6. Effect of Pressure on the Anneal of Quenched-In Vacancies in Gold.* R. M. EMRICK AND D. LAZARUS, *University of Illinois.*—The effect of pressure on the annealing rate of vacancies quenched in gold has been studied. High purity gold wires were quenched from the region of 700°C and placed in a pressure vessel capable of producing 10 000 atm hydrostatic pressure. The annealing kinetics were reasonably close to first order during the first 80% of the anneal of the quenched-in resistance. Absolute reaction rate theory was used to calculate a volume of motion. The small value of this motional volume was consistent with the small activation volumes resulting from pressure effect studies on self-diffusion in bcc metals[1] and fcc metals.[2] Long anneal times, however, resulted in significant deviations from first-order kinetics. The measuring technique was not sufficiently sensitive to determine the nature of the kinetics at the lower vacancy concentrations.

* Supported in part by the U. S. Atomic Energy Commission.
[1] N. H. Nachtrieb, J. A. Weil, E. Catalano, and A. W. Lawson, J. Chem. Phys. **20**, 1189 (1952). N. H. Nachtrieb and A. W. Lawson, J. Chem. Phys. **23** (1955).
[2] N. H. Nachtrieb, H. A. Resing, and S. A. Rice, J. Chem. Phys. **31**, 135 (1959).

OA7. Self-Diffusion in Silver under Hydrostatic Pressure up to 8000 atm.* C. T. TOMIZUKA,† R. C. LOWELL, AND A. W. LAWSON, *University of Chicago.*—It is generally accepted that the activation volume for self-diffusion is closely related to the actual volume of a mole of moving vacancies. Experimental determination of the activation volume for self-diffusion was successfully carried out in lead, sodium, and white phosphor earlier by Nachtrieb and his co-workers. Similar experiments in noble metals would yield quantitative information regarding the nature of defects responsible for diffusion. In view of the requirement of high temperature the present experiment was carried out in a pressurized argon gas system. The standard tracer techniques and lathe sectioning procedure were used for the determination of diffusion coefficients. The results so far obtained on silver single crystals indicate that the amount of relaxation of atoms surrounding a vacancy is somewhat

smaller than that which is consisted to exist in other materials and than the amount expected from existing theories.

* This work was partly supported by Office of Naval Research and Air Force Office of Scientific Research.
† Present address: Department of Physics, University of Arizona, Tucson.

OA8. Feasibility of Quenching Lattice Defects in Noble Metals under Hydrostatic Pressure.* R. C. LOWELL, AND C. T. TOMIZUKA,† *University of Chicago.*—In order to investigate the possibility of determining the activation volume for the formation of point defects in metals directly through a series of quenching experiment as a function of hydrostatic pressure, a natural cooling rate of a heated platinum wire was measured under pressure up to 8500 atm. It was found that the quenching rate from 1050°C was reasonably constant in the pressure range of 3000 to 8500 atm. The observed quenching rate of 10^4 deg/sec is sufficiently large to permit the proposed experiment.

* Supported in part by the Office of Naval Research and the Air Force Office of Scientific Research.
† Present address: Department of Physics, University of Arizona, Tucson.

OA9. Quenched-In Vacancies and Quenching Strains in Gold. JIN-ICHI TAKAMURA,* *University of Chicago* (introduced by C. S. Barrett).—The contraction in length of quenched gold specimens (99.999% purity, 1 to 2 mm in diam and 100 mm in length) was observed during annealing at room temperature. The concentration C of quenched-in vacancies can be given by $\alpha C=\Delta V/V=A\exp(-E/kT)$, where α is the fractional volume of a vacancy, $\Delta V/V$ the total volume change deduced from the length measurements, E the formation energy, T the quenching temperature, and A the entropy term. Experimentally, the values of A and E vary with the specimen radius as $A=A_0\exp(-ar^2)$ and $E=E_0-br^2$, where $A_0=1.39$, $E_0=0.98$ eV, $a=157$ mm^{-2}, and $b=0.17$ eV·mm^{-2}. Adopting for A_0/α the published value 3.2, α is found to be 0.43. The dependence of A and E on the specimen size is related to the time required for quenching and to quenching strains. The concentration of vacancies caused by quenching strains was found to be quite large, for example, 8.8×10^{-5} for 2-mm diam specimens and 0.6×10^{-5} for 0.4-mm diam specimens quenched from 800°C, corresponding, respectively, to 84.6% and 7.4% of the total vacancies in the specimen.

* On leave from Department of Metallurgy, Kyoto University, Japan.

OA10. Mechanical and Electrical Resistivity Studies on Vacancies Quenched from below 800°C in Gold.* T. MORI, M. MESHII, AND J. W. KAUFFMAN, *Northwestern University.*—Studies on the nature of vacancy sinks and the mechanism of hardening are made for quenches below 800°C in pure gold. There are two general possibilities: (1) The majority of vacancies form clusters and the mechanism of hardening is due to the result of clustering; (2) vacancies are mainly absorbed by dislocations. The magnitude of binding energy of vacancy may be the decisive factor of the above selection. The present results indicate that the first mechanism operates. Over the whole range of quenching temperatures investigated, no appreciable overaging is detected. An increase in yield stress and a decrease in resistivity occur simultaneously in the same fashion.

* Supported by the Office of Naval Research.

OA11. Vacancy Migration and Coagulation in Quenched Gold.* M. MESHII, T. MORI, AND J. W. KAUFFMAN, *Northwestern University.*—An increase of resistivity is observed initially upon annealing after quenching from below 500°C.[1] A maximum resistivity may occur for clusters of diameter about the size of the wavelength of the conduction electrons. For quenches above 500°C appreciable clustering has occurred during quenching, and therefore no increase is observed. The time to reach the maximum in resistivity is found to be dependent on the quenching temperature, and hence on the concentration of lattice vacancies. A simple model can explain the dependence of the time to reach maximum resistivity on quenching temperature. Using this model the data give 0.9 ev as the formation energy. The usual method for determining the formation energy of lattice vacancies is to plot the log of quenched-in resistivity against $1/T$. For quenches below 500°C the initial quenched-in resistivity begins to deviate below this curve, but fits on this straight line provided one takes the extrapolated value from the lower part of the resistivity recovery curve extrapolated to zero time. The migration energy was determined over a wide range of annealing times and quenching temperatures. The binding energy between vacancies obtained is 0.3 ev or greater.

* Supported by U. S. Office of Naval Research.
[1] M. Meshii, T. Mori, and J. W. Kauffman, Bull. Am. Phys. Soc. Ser. II, 4, 455 (1959).

OA12. Self-Diffusion in 50-50 Gold Cadmium Alloy.* H. B. HUNTINGTON, N. C. MILLER, AND V. NERSES,† *Rensselaer Polytechnic Institute.*—Self-diffusion studies have been carried out on the 50-50 Au-Cd alloys using radioisotopes Cd_{117} and Au_{198}. The results for the diffusion of cadmium are well fitted with the values $Q=29.8$ kcal/mole and $D_0=0.75$ cm²/sec over the temperature range 300° to 610°C. Over the same range the analogous values for the gold were $Q=27.9$ kcal/mole and $D_0=0.1_5$ cm²/sec. At the highest temperature there was some evidence of deviation. This alloy appears to be ordered up to the melting point. The two diffusion plots practically superimpose in the lower part of temperature range, a fact which, in an ordered alloy, strongly suggests nearest neighbor vancancy jumping as the dominant mechanism for atom movement. The activation energies for self-diffusion lie above the value predicted from resistivity measurements on quenched specimens by Wechsler[1] who found an energy for defect motion of 13.4 kcal/mole and an energy of formation of 8.7 kcal/mole. If the moving defect is indeed the vacancy, then it would appear that some other cause must be sought for the extra quenched-in resistivity, perhaps short-range disorder which is later eradicated by the vacancy motion.

* Supported by the U. S. Atomic Energy Commission.
† Now at Nuclear Metals, Inc.
[1] M. S. Wechsler, Acta Met. 5, 150 (1957).

OA13. Flux Dependence of Enhanced Diffusion in α-Brass.* R. E. LARSEN,† A. C. DAMASK,‡ AND G. J. DIENES, *Brookhaven National Laboratory.*—Diffusion in some metals proceeds by the vacancy mechanism. Neutron irradiation produces a higher than equilibrium defect concentration and thereby enhances diffusion. A simple theory proposed by Dienes and Damask[1] predicts that if the defects anneal to fixed sinks during irradiation, enhancement of diffusion is temperature independent and proportional to the flux. Previous experiments showed that the neutron enhanced diffusion coefficient of α-brass is temperature independent from 0°C to 150°C, in agreement with theory. An investigation of the flux dependence has been completed recently, in cooperation with Los Alamos, using a nuclear rocket engine as a neutron source. Identically prepared brass wires were simultaneously irradiated at different distances from the engine, thereby in different fluxes, at 60°C. Electrical resistivity changes, reflecting short range ordering by enhanced diffusion, were measured. Diffusion constants calculated from the resistivity relaxation times were essentially linear in the flux, in agreement with the simple theory.

* Supported in part by the U. S. Atomic Energy Commission.
† Guest Scientist from Frankford Arsenal.
‡ Supported by a U. S. Secretary of the Army Fellowship.
[1] G. J. Dienes and A. C. Damask, J. Appl. Phys. 29, 1713 (1958).

OA14. Diffusion of Gold in Lead.* A. ASCOLI† AND A. C. DAMASK,† *Brookhaven National Laboratory.*—The diffusion of gold into lead was measured on lead single crystals (99.999%) with about 1000 atomic layers of Au^{195} plating. After the annealings the specimens were sectioned (20-μ slices) and the

resulting K x-ray activity from the Pt decay product was measured. The results are $Q=9.3$ kcal/mole and $D_0=4\times10^{-3}$ cm²/sec. If Q for self-diffusion in lead is accepted as 23–28 kcal/mole, then an interpretation requires a very high binding energy of a vacancy to an old atom. Another explanation is that the lead atom deviates towards the gold during its jump. Thus the repulsive terms opposing its motion can be reduced, and hence the activation energy lowered for the motion of the "Johnson molecule." This deviation would require either that (1) the minimum of the pairwise potential for the lead-gold interaction be at a smaller distance than the corresponding quantity for the lead-lead interaction or (2) the slope of the repulsive interaction be less for gold-lead than for lead-lead.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Guest Scientist from C.I.S.E. Laboratories, Milan, Italy.
‡ Supported by U. S. Secretary of the Army Fellowship.

TUESDAY AFTERNOON AT 2:15

Lecture Hall, Institute of Arts

(R. S. HALFORD presiding)

Symposium of the Division of Chemical Physics

P1. Magnetic Rotation Spectra of Singlet-Triplet Transitions. H. E. EBERHARDT, *Georgia Institute of Technology.* (45 min.)

P2. Stark Effects in Molecular Vibration-Rotation Spectra. C. W. PETERS, *University of Michigan.* (45 min.)

P3. Inelastic Scattering of Electrons in Gases. A. N. LASSETTRE, *Ohio State University.* (45 min.)

Business Meeting of the Division of Chemical Physics

(to be held during the session whenever the Chairman chooses)

TUESDAY EVENING AT 7:00

Banquet Hall of the Engineering Society of Detroit

(V. F. WEISSKOPF presiding)

Banquet of The American Physical Society

(after-dinner speakers to be announced)

WEDNESDAY MORNING AT 9:30

Auditorium, Institute of Arts

(V. F. WEISSKOPF presiding)

DSSP Symposium on Electronic States of Metals

Q1. Determination of the Fermi Surfaces of Metals. M. H. COHEN, *University of Chicago.* (40 min.)

Q2. Spectroscopic Methods of Investigating Band Structures of Metals. J. K. GALT, *Wayne State University.* (30 min.)

Q3. Existence of a Fermi Surface in Metals. J. M. LUTTINGER, *University of Pennsylvania.* (30 min.)

Q4. Nuclear Resonance in Ferromagnetics. A. M. PORTIS, *University of California.* (30 min.)

WEDNESDAY MORNING AT 9:30

Lecture Hall, Institute of Arts

(G. J. DIENES presiding)

Irradiation Effects: Alkali Halides

QA1. Electron-Nuclear Double Resonances in Irradiated KCl. W. E. BLUMBERG AND G. FEHER, *Bell Telephone Laboratories.*—We have observed by the ENDOR technique nuclear resonance lines in irradiated KCl which we attribute to the nuclei surrounding the F-centers. The experiments were performed at 1.3°K and 9400 Mc/sec. Groups of lines

exhibiting isotropic and anisotropic hyperfine coupling (a and b as defined in reference 1) have been assigned to the five shells of nuclei near the F-center as follows:

Position	Nucleus	a/h, Mc/sec	b/h, Mc/sec
(100)	K^{39}	21.5	0.91
(110)	Cl^{35}	6.9	0.50
(111)	K^{39}	0.31	0.032
(200)	Cl^{35}	1.06	0.11
(211) (tentative)	Cl^{35}	0.10	0.03

The lines assigned to the nuclei in the (100) and (110) positions show an additional nuclear quadrupole splitting as previously reported.[1] The highest frequency K^{39} lines exhibit a further splitting attributed to a second order spin-spin coupling via the isotropic hyperfine interaction. These hyperfine splittings suggest new approaches to the F-center wave function problem which will be discussed.

[1] G. Feher, Phys. Rev. **105**, 1122 (1957).

QA2. Defects Induced in NaCl and KCl by Reactor and Gamma-Ray Irradiations.* PAUL W. LEVY, *Brookhaven National Laboratory.*—In NaCl and KCl crystals exposed to reactor radiations one can separate the defect production by fast neutrons from the effects of the purely ionizing radiation component. This is accomplished by first coloring with gamma rays, then reactor irradiating for short periods such that the in-pile coloration dose is small compared to the original dose and then resuming the gamma-ray coloring. Gamma-ray coloring curves rise rapidly at low doses and then level off; from this and from simple kinetic considerations one concludes that the gamma-ray irradiations have colored all (or an equilibrium fraction) of the defects present. Reactor irradiations increase markedly the F, V, M, R, and other bands, and the absorption from 3 to 6 ev. For reactor irradiations of 30 min or less the subsequent gamma-ray coloring continues at an increased level with the original slope. With longer reactor irradiations the subsequent coloring first produces a twofold increase, then a decrease, and finally increases at a higher level with roughly the original slope. The number of vacancies produced by short reactor irradiations, determined from the F-center coloring, agrees well with the theories of Kinchin and Pease and Seitz and Koehler.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

QA3. Coloring of NaCl and KCl by Co^{60} Gamma Rays.* BERNARD MOZER AND PAUL W. LEVY, *Brookhaven National Laboratory.*—When NaCl and KCl are exposed to Co^{60} gamma rays, with all samples kept in darkness at 25°C, one obtains prominent F-center coloring, less intense V, M, and other centers, and a very broad absorption extending from 3 to 6 ev. Some F-center growth curves, particularly for unstrained samples, rise rapidly to a plateau, level off, and then rise slowly into a long linear region. It is suggested that the initial stage represents coloring of existing vacancies and the second stage represents the coloring of vacancies formed during irradiation. In both stages the character of the curves depends on various factors, especially heat treatment and the degree of strain the sample may have been subjected to prior to irradiation. Even virgin crystals show large variations between crystals, probably related to impurities and crystal history. However, similar growth curves can be obtained with different dose rates especially below 1.7×10^5 r/hr. Part of the induced color decays, after exposure, with at least two unstable components whose magnitude is a function of F-center density. Curves of color center density versus decay time follow a "radioactive decay" law. At large color center concentrations some of the faster decaying components are not observed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

QA4. Damage Effects of 40-Mev Alpha Particles on Sodium Chloride. M. HACSKAYLO, *NASA Lewis Research Center.*—The bombardment of sodium chloride crystals with 40-Mev alpha particles induces a plane of high damage at the end range of the particles. This damage is discernible at fluxes greater than 10^{14} particles per cm^2. Upon annealing the crystal at a temperature of 400°C for five minutes, a light scattering planar region appears at the end range. This planar region is composed of cubic bubbles 50 μ on edge and the bubbles are oriented with the crystal axes. Chemical analyses of the crystals which were bombarded with 5×10^{15} particles per cm show that the colored portion contains 2×10^{18} per cm^3 of "free chlorine" and 1.6×10^{18} per cm^3 of "free sodium."[1,2] However, upon annealing the "free chlorine" and "free sodium" recombine so that neither are measurable. Helium gas was detected in the bombarded sample, but not in the annealed state. It appears that the bubbles are connected with the high damage effects at the end range of the alpha particles.

[1] M. Hacskaylo and D. Otterson, J. Chem. Phys. **2**, 552 (1953).
[2] M. Hacskaylo, D. Otterson, and P. Schwed, J. Chem. Phys. **21**, 1434 (1953).

QA5. F-Center Formation in KCl.* P. V. MITCHELL, D. A. WIEGAND, AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.*—A detailed study has been made of the rate of F-center formation in KCl and NaCl due to x-ray irradiation at room temperature. Depending upon irradiation conditions, the curve of F-center density vs time of irradiation may or may not have an inflection point. This curve can be described very accurately by an equation containing the following parameters: the probability for capture of electrons at negative ion vacancies in the lattice before irradiation; the capture probability of electrons at negative ion vacancies created during the irradiation; the density of negative ion vacancies in the lattice before irradiation; and the probability for generation of new negative ion vacancies. The capture probability at vacancies in the lattice before irradiation is found to be roughly a factor of 20 larger than the capture probability at newly created vacancies. The intensity dependence of the above parameters has been investigated and the probability of generation of negative ion vacancies is found to increase with the square of the intensity.

* Research supported by a U. S. Atomic Energy Commission and an Office of Naval Research contract.

QA6. Influence of Cold Work and Heat Treatment on F-Center Formation in KCl.* D. A. WIEGAND, P. V. MITCHELL, AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.*—An analysis of the growth curve of F centers produced by x-ray irradiation at room temperature permits differentiation between centers formed from vacancies existing before irradiation and those formed from vacancies created during irradiation (see previous abstract). Influence of prior plastic deformation and heat treatment upon the two processes has been investigated. It appears that both, deformations (up to 3%) and quenching from 500°C, increase the total number of F centers formed from vacancies existing before irradiation. The rate of capture of electrons is, however, different in these two cases and agrees with the suggestion that cold work produces vacancies near dislocations, while quenching increases the concentration of vacancies throughout the crystal volume. Cold work appears to lower the rate of creation of new vancancies by irradiation.

* Research supported by a U. S. Atomic Energy Commission and an Office of Naval Research contract.

QA7. Defect Formation in LiF by Ionizing Radiation.* R. SMOLUCHOWSKI AND D. A. WIEGAND, *Carnegie Institute of Technology.*—The formation of defects in LiF as a result of ionizing irradiation has been investigated as a function of intensity, temperature, and plastic deformation. The data

indicate that in contrast to KCl and NaCl (see previous abstracts) the growth curves of F centers at 90° and 300°K in LiF are a function only of total dose received and not intensity or plastic deformation. This result will be discussed in terms of possible kinetics of defect formation. Annealing studies indicate that the temperature at which damage is removed is a function of the sample temperature during irradiation. Possible reasons for this will also be discussed.

* Research supported by a U. S. Atomic Energy Commission and an Office of Naval Research contract.

QA8. Measurement of Stored Energy in X-Irradiated Sodium Chloride.* FRED T. PHELPS AND EDGAR A. PEARLSTEIN, *University of Nebraska.*—The stored energy associated with x-ray absorption in sodium chloride is measured by comparing the heats of solution of two sodium chloride samples, one of which is x-irradiated but otherwise equal to the other. The differential calorimeter used consists of two nearly identical copper containers mounted in an evacuated chamber in such a way that they can be rotated parallel to each other to provide the necessary mixing action. The temperature difference of the two containers is measured using copper-Constantan thermocouples, a microvolt potentiometer, dc amplifier, and recording milliammeter. Furthermore, the temperature of one container is monitored so the heat of solution of sodium chloride can be determined, thus providing an independent check on each run. Stored energy is measured as a function of F-center density, which is determined from the F absorption band. Preliminary measurements indicate that the stored energy in x-irradiated sodium chloride is approximately 60 ev per F center at a coloration density of 2×10^{17} F centers per cm³.

* This research supported in part by the U. S. Atomic Energy Commission.

QA9. Increase in Thermal Expansion Coefficient of X-Rayed NaCl.* M. F. MERRIAM, D. A. WIEGAND, AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.*—The thermal annealing of the radiation induced volume expansion of NaCl heavily irradiated with 300-kvp x rays has been studied above room temperature, using a photoelastic technique in which half the crystal is irradiated and the resulting volume expansion deduced from the strain in the unirradiated portion. An apparent linear increase in $\Delta V/V$, relative to the unirradiated portion, is observed as the temperature is raised from room temperature to 200°C. It is unlikely that this is caused by motion of defects, since $\Delta V/V$ recovers reversibly to its original value if the temperature is lowered. Also, a more direct measurement[1] shows no change in $\Delta V/V$ over this temperature range. The temperature dependence of the elastic and photoelastic constants used in the calculation has been checked. It is concluded that the observed effect reflects a difference in thermal expansion coefficients of the two halves of the crystal $\Delta\alpha/\alpha\sim0.0025$; the expansion coefficient of one-half having been increased by irradiation. Implications for models of radiation damage in alkali halides will be discussed.

* Research supported by a U. S. Atomic Energy Commission and an Office of Naval Research contract.

[1] K. Kobayashi, Phys. Rev. 107, 41 (1957).

QA10. Dislocation Pinning in Rock Salt Caused by X-Irradiation.* C. L. BAUER AND R. B. GORDON, *Yale University.*—An increase in the elastic modulus of plastically deformed rocksalt due to dislocation pinning has been observed during x-irradiation at temperatures ranging from 77° to 300°K. The rate at which the modulus change occurs during irradiation is independent of temperature and curves showing the normalized modulus change as a function of x-ray dose at different temperatures are nearly identical. The irradiation effect at 77°K is qualitatively different from that occurring at 196°K or higher temperatures in that after the saturation value of the modulus has been reached at low temperature, irradiation at room temperature produces an additional modulus increase. Explanations of the pinning action of x irradiation based on the diffusion of the ordinary structure defects in rocksalt to dislocations appear to be ruled out by the rapidity of the low temperature modulus change. At temperatures of 0°C or above it is observed, however, that the modulus increase continues for a short time after the x-ray source is turned off (provided that the effect has not been brought to saturation) and that optically bleaching a partially irradiated crystal causes a further modulus increase.

* Supported by the National Science Foundation.

QA11. Mechanism for Coloration of Alkali Halides at Low Temperatures. CLIFFORD C. KLICK, *U. S. Naval Research Laboratory.*—A model for low temperature coloration of alkali halides is proposed in which double ionization of a halide ion leads to the formation of an uncharged halogen molecule which occupies two neighboring halide ion sites. If the molecule is localized at one of these sites by the jump of a nearby halide ion into the other site, a vacancy and interstitial are formed. Capture of an electron by each of these imperfections would lead to the production of the F center and H center.

QA12. Dependence of the Optical Bleaching Rate of X-Irradiated KCl on Light Intensity. W. E. BRON AND W. R. HELLER, *IBM Yorktown Research Center.*—Measurements have been made on the changes in the initial bleaching rate of F centers as the result of varying the intensity of F light. KCl crystals were used which contain about 3×10^{16} F centers/cm³ after irradiation with hard x rays at room temperature. The total bleaching of F centers during the first ten seconds of illumination varies approximately linearly with light intensity at low intensities, but becomes saturated at intensities greater than 5×10^{14} photons/sec/cm². Using reasonable values for photoelectron capture cross sections forces one to conclude that the initial bleaching involves the capture of photoelectrons primarily at pre-existing electron traps. This means that photoelectrons exist only briefly in the conduction band, and the resulting simplification of the analysis leads to prediction of the experimentally observed variation of bleaching rate with light intensity. The analysis shows that the ratio of the capture cross section for photoelectrons of the electron trapping centers to that of negative-ion vacancies is between 1 and 3, which strongly suggests that the trapping centers are either traps with net negative charge or are neutral traps located close to the original F centers.

QA13. Colloids in Additively Colored Sodium Chloride. H. W. ETZEL, *United States Naval Research Laboratory.*—A study has been made of the formation of colloids in additively colored sodium chloride. Both natural and synthetic single crystals were additively colored by heating in a vapor of sodium and by injecting electrons from a point cathode. The crystals were slowly cooled from the additive coloring temperature. Subsequent irradiation with ultraviolet light and heating of the synthetic crystals produced an absorbing type colloid throughout the crystal. The same treatment applied to the natural crystals produced F centers throughout the bulk of the crystal and absorbing type colloid specks at localized points in the crystal. In the synthetic crystals the formation of these colloids is shown to be related to the presence of hydroxyl ions in the crystals prior to coloration. In the natural crystal the formation of such colloids is dependent upon the presence of small occlusions of water distributed randomly in the crystal prior to coloration.

QA14. Effect of Mono- and Trivalent Cations on Color Centers in Calcium Fluoride.* W. J. SCOULER AND A. SMAKULA,

Massachusetts Institute of Technology.—Coloration of pure CaF_2 crystals with 2.5-Mev electrons at room temperature gives the usual four bands, located at 580, 400, 335, and 225 mμ. Low-temperature (−190°C) coloration, however, yields different bands located at 550, 320, and 270 mμ. In YF_3-doped crystals the bands are in the same spectral positions as in pure crystals. They are, however, enhanced, and at room temperature their intensity ratios are significantly changed, the 400-mμ band being predominant. NaF-doped crystals show an even more drastic change. Coloration at room temperature produces bands located at 605, 385, and 330 mμ, while at −190°C it yields bands at 440, 385, 315, and 200 mμ. The coloration in NaF-doped crystals is deeper than in either pure or YF_3-doped crystals. Several explanations are possible for the modification of the color center spectra by doping: (1) In YF_3-doped crystals, interstitial F^- ions may act as a source of electrons and holes and/or induce vacancy formation through lattice distortion. (2) In NaF-doped crystals, F^- vacancies may act as traps and/or enhance oxygen contamination by diffusion.

* This research was supported by the Office of Naval Research.

WEDNESDAY MORNING AT 9:30

WSU McGregor Memorial

Conference Center Room L

(G. C. DANIELSON presiding)

Compound Semiconductors II, and others

R1. Anomalous Hall Effect in $AgSbTe_2$. R. WOLFE, J. H. WERNICK, AND S. E. HASZKO, *Bell Telephone Laboratories.*—The Hall coefficient of the ternary semiconductor $AgSbTe_2$ near room temperature is positive in some specimens and negative in others, although the Seebeck coefficient is always positive. The negative Hall coefficient decreases as the temperature is lowered from 180°K to 70°K and changes sign at lower temperatures. This negative Hall coefficient is associated with the presence in the $AgSbTe_2$ of a second phase consisting of Ag_2Te. The properties of the two-phase material are interpreted in terms of the theory of the transport properties of inhomogeneous semiconductors. In single phase $AgSbTe_2$ containing 3×10^{19} holes per cm^3, the hole mobility is 35 cm^2/volt sec at 300°K and it varies approximately as $T^{-\frac{1}{2}}$. The lattice thermal conductivity is so low (0.0064 watt/cm°C at 290°K) that the calculated "phonon mean free path" is less than the nearest neighbor distance. The thermal conductivity of a specimen rich in $AgSbTe_2$-Ag_2Te eutectic is higher than that of either of the components. This excess thermal conductivity is attributed to circulating thermoelectric currents.

R2. Cadmium Sulfide Surface Noise.* JAMES J. BROPHY, *Armour Research Foundation.*—Previous measurements of current noise and photoconductivity of CdS single crystals to determine the frequency factor and energy distribution of shallow traps have been extended by using 4400 A illumination to obtain results characteristic of the crystal surface. The noise data determine the depth to which electron-hole pairs diffuse, 30 microns, which is in good agreement with the ambipolar diffusion length recently reported,[1] and establish that the energy depth of the discrete traps below the conduction band is the same in this surface region as in the bulk of the crystal. The current noise spectra follow a $f^{-\frac{1}{2}}$ diffusion law[2] until retrapping noise becomes dominant at about 550 cps. Experimentally determined transition frequencies are in good agreement with those predicted from the photoconductive time constants. Trap densities in the surface regions are an order of magnitude greater than those in the bulk and the frequency factors are in the range 10^8 to 10^9 sec^{-1}.

* Supported by the Office of Naval Research.

[1] J. Auth and R. Ridder, Ann. Phys. (Leipzig) **2**, 351 (1959).

[2] M. Lax and P. Mengert, Second Conference on Semiconductor Surfaces, December, 1959.

R3. Noise in InSb Photodiodes. B. R. PAGEL, *Texas Instruments Incorporated.*—Experimental investigations were made of the noise generation in seven InSb infrared photovoltaic solid-state diodes operated at 77°K. The noise was measured with the photodiodes viewing only the infrared radiation of a black-body cavity at room temperature. The object of the experiment was to compare the total measured noise with the noise component generated by the background radiation. This latter component is associated with the random incidence of photons on the detector. It is calculated from the relation $\langle i^2\rangle/\Delta f = 2qI_{PH}$ where I_{PH} is the photoinduced current which is measured directly by biasing the diode to zero potential. Measurements of the total noise generated in the photodiodes as a function of the bias current through the diodes showed that the noise is a minimum when the detector is biased to zero voltage. The noise character of the detectors when biased to zero voltage were then studied in detail by measuring the spectra to obtain the white noise level. The measurements showed that generally there was no excess noise at one kilocycle or above and that the white noise in InSb photodiodes is almost wholly attributable to the noise generated by the background infrared radiation. The measured values were of the order of only one decibel above the theoretical value.

R4. Bridge for Evaluating Contacts to Photoconductors. D. R. BOYD AND Y. T. SIHVONEN, *General Motors Corporation.*—An arrangement wherein a photoconducting crystal having three contacts, two of which are to be examined, becomes part of a low frequency bridge has been developed to aid in contact studies. Analysis and experiment with CdS shows that under certain conditions, an absolute qualitative determination can be made of individual contact behavior, i.e., ohmic or diodic, whereas previously only relative comparisons have been possible. The bridge makes use of special high input impedence circuitry in order to accommodate low conductance specimens (10^{-8} mhos). Contact characteristics are displayed for interpretation of an oscilloscope.

R5. Carrier Lifetimes by the PEM Method. R. W. CUNNINGHAM, *Texas Instruments Incorporated.*—Preliminary PEM measurements have been carried out on InSb as part of a program to study carrier lifetimes in semiconductors. The experimental technique is similar to that used elsewhere.[1] The equipment was constructed in such a way that mobility-

diffusion length products of the order of 10^{-9} meter^3-volt^{-1} sec^{-1} could be detected at moderate magnetic fields. Illumination obtained from either a broad band or line source was chopped at a frequency of 570 cps. Photon densities were computed from the response of a calibrated thermocouple. During the measurements the sample was in vacuum. Deviations from simple two carrier theory were observed for p-type InSb. A case intermediate to both the high and low surface recombination approximations was observed. By suitable analysis a value for the diffusion length may be obtained. A more elaborate theory taking into account band edge distortions near the surface may explain the deviations from the simpler theory for p-type InSb.

[1] R. N. Zitter, A. J. Strauss, and A. E. Attard, Phys. Rev. **115**, 266 (1959).

R6. Very Low Frequency Excitation of Electroluminescence. W. J. FREDERICKS, *Stanford Research Institute.*—A study has been made of electroluminescence brightness waves produced by very low frequency excitation. A symmetrical sawtooth voltage was applied to electroluminescence cells of a ZnS, ZnO: Cu, Ag, Cl phosphor. Measurements of the brightness waveforms and phase as a function of excitation frequency in the range from 0.02 cps to several hundred cps, and in temperature range from 273°K to 450°K have been made on cells with the phosphor embedded in a slightly conducting medium so that the average field across the phosphor was approximately equal to and in phase with the average field applied to the cell.[1] At low excitation frequencies the emission of this phosphor is predominately in a green band at 5200 A. At room temperature with low frequency excitation the maximum in the brightness wave occurs before the voltage maximum. As the excitation frequency is increased the brightness wave maximum occurs later with respect to the excitation voltage, and finally follows the voltage maximum. As the temperature is increased the brightness wave maximum occurs earlier in time. These results are consistent with Morehead's[2] description of the electroluminescent process.

[1] P. Zalm, Philips Research Repts. **11**, 353 (1956).
[2] F. F. Morehead, J. Electrochem. Soc. **105**, 461 (1958).

R7. Resistivity of Sodium Tungsten Bronze.* L. D. ELLERBECK,† P. H. SIDLES, AND G. C. DANIELSON, *Iowa State University.*—Sodium tungsten bronzes are nonstoichiometric compounds with the chemical formula Na_xWO_3. Large single crystals have been prepared in the range $0.48<x<0.88$ by an electrolytic method. Samples for electrical resistivity measurements were cut from these single crystals, were well annealed, and were selected for uniformity in resistivity around their periphery and along their length. At room temperature the electrical resistivity of these homogeneous samples was found to decrease monotonically from 69 μohm-cm at $x=0.48$ to 16 μohm-cm at $x=0.88$. Up to 650°C the resistivity data exhibited metallic character. Earlier investigators[1] have reported a resistivity minimum at $x=0.75$. We have found no minimum for homogeneous crystals and believe the minimum observed by others was caused by inhomogeneities which resulted from the growth habit of these bronzes. These inhomogeneities tend to predominate at the ends of the cubic range and always increase the resistivity, so that a minimum in the curve of resistivity vs x is obtained when samples are selected at random.

* Work done in the Ames Laboratory of U. S. Atomic Energy Commission.
† Now at University of Omaha.
[1] B. W. Brown and E. Banks, Phys. Rev. **84**, 609 (1951); W. R. Gardner and G. C. Danielson, Phys. Rev. **93**, 46 (1954).

R8. Decay of Persistent Polarization in Diamond.* J. A. ELMGREN AND D. E. HUDSON, *Iowa State University.*—The decay of the internal field created by trapped charges in a diamond (partially Type I) has been studied by utilization of the counting rate, with no external field applied, as a probe of the internal field. The decays induced by thermal excitation and by photons of seven energies in the range from 2.14 to 3.40 ev have been investigated. The effect of photon flux density was determined at each photon energy. The observed dark decay appears to be a result of two energy levels at thermal depths of approximately 0.5 and 0.6 ev. An optical band around 3 ev was found to be very active in decay, with an estimated charge liberation cross section of the order of 10^{-14} cm^2. This same band is found in the absorption spectrum of Type I diamond.[1] The large cross section tends to support the aggregate vacancy model of this system proposed by Champion.[2]

* Supported in part by the U. S. Atomic Energy Commission.
[1] C. D. Clark, R. W. Ditchburn, and H. B. Dyer, Proc. Roy. Soc. (London) **A234**, 363–381 (1956).
[2] F. C. Champion, Proc. Roy. Soc. (London) **A234**, 541–556 (1956).

R9. Luminescence in Semiconducting Diamond.* J. B. KRUMME AND W. J. LEIVO, *Oklahoma State University.*—Various forms of luminescence in semiconducting diamond were investigated in order to correlate the results with other known properties of the same specimens. Ultraviolet light induced blue luminescence[1] was observed in the investigated temperature range of 90°K to 430°K, and the spectrum extended from 375 mμ to 615 mμ with a maximum at 480 mμ at 300°K. The temperature dependence of the luminescent intensity indicated that the luminescence is a phosphorescence rather than a slow fluorescence. One specimen has a blue region and a clear region, and in the former the luminescence is considerably more intense, the electrical conductivity much higher and the photoconductive response different from that in the clear region. Both regions are p-type semiconductors. Electroluminescence and triboluminescence were observed in all specimens. An unusual red luminescence with a longer lifetime than the blue luminescence was found in two of the samples. The red luminescent intensity which is quite low at room temperature increases with increasing temperature being already quite apparent at 360°K, thus implying a phosphorescent process.

* This work was supported by the U. S. Air Force Office of Scientific Research.
[1] For an early report of the blue luminescence see J. F. H. Custers, Physica **18**, 489 (1952).

R10. X-Ray Study of Pyrographite.* O. J. GUENTERT AND C. T. PREWITT,† *Raytheon Company.*—In a preliminary investigation, pyrographite samples, which has been deposited at different temperatures ranging from approximately 1700°C to 2500°C, have been studied by x-ray diffraction methods. The basically polycrystalline material was found to consist of groups of parallel and approximately equidistant graphite layers with random layer orientation at the lower deposition temperatures and partial layer order at higher temperatures. The average layer group dimension is of the order of 50 A at 1700°C and increases to about 500 A at 2500°C. The increase in the size and layer order with increasing temperature is accompanied by a reduction of the layer spacing from 3.43 A at 1700°C to 3.35 A at 2500°C. All samples exhibit preferred orientation in which the layers of the individual layer groups tend to align themselves parallel to the face of deposition. This preferred orientation of the bulk samples increases strongly with increasing deposition temperature.

* Supported by the Special Projects Office of the Bureau of Naval Weapons, Department of the Navy.
† Present address: Massachusetts Institute of Technology.

R11. Galvanomagnetic Properties of Pyrographite. CLAUDE A. KLEIN, *Raytheon Company.*—Galvanomagnetic data have been taken on specimens of pyrographite deposited at temperatures ranging from 1700 to 2600°C. These data are presently being analyzed. Attention has been focused on (1) *Resistivity:* at room temperature, the ratio of conductivities in the (a,b) and (c) directions[1] of our better samples exceeds 2000, with a resistivity in the hard direction of 0.5 ohm-cm. The temper-

ature coefficients appear to be negative in the investigated temperature range, i.e., 50° to 1250°K. (2) *Magnetoresistivity:* room temperature resistivities were measured with applied transverse magnetic fields of 2 to 25 kgauss. A rather pronounced magnetoresistance effect of the type $\Delta\rho/\rho = CH^x$, with $1 < x < 2$, occurs in the basal plane and provides indications on the carrier mobilities. (3) *Hall effect:* specimens deposited at or above about 2500°C appear to be *n*-type. In all other cases, it seems that the conduction process in the basal plane is determined by holes with concentrations of the order of 10^{19} cm^{-3}. Considering the negative temperature coefficient of both the resistance and the Hall response, this might be interpreted as indicating that pyrographite deposited at lower temperatures is "damaged"—the damage centers acting as electron traps. Such an interpretation is also supported by measurements made on samples which were "annealed" at very high temperatures.

[1] See preceding abstract.

R12. Optical Properties of Pyrographite. G. RUPPRECHT, *Rayiheon Company.*—The high anisotropy of structural and electrical properties of pyrographite causes an anisotropy of the optical absorption. In the "hard direction," the crystallographic *c* axis, the optical transmission could be measured on thin samples which have been prepared in such a way that the plane exposed to the incident light contains the *a* axis and the *c* axis. In the infrared range from 3 to 15 μ the absorption can be explained in terms of a free carrier absorption. The absorption coefficient can be calculated tentatively from the conductivity σ on the basis of a free carrier conductivity model. It appears that the conductivity obtained by optical measurements is in satisfactory agreement with the results of dc measurements. Since the conductivity in the basal plane exceeds the conductivity in the hard direction by a factor of 10^3, pyrographite provides a new and effective means of polarizing infrared light.

WEDNESDAY MORNING AT 9:30

Auditorium, Rackham Memorial

(J. E. GOLDMAN presiding)

Invited Paper

RA1. Optical Properties of Some Transition-Metal Monoxides. R. NEWMAN, *Hughes Aircraft Company.* (30 min.)

Magnetism: Experimental

RA2. Antiferromagnetic Domains and Magnetic Susceptibility in NiO Crystals, W. L. ROTH AND G. A. SLACK, *General Electric Research Laboratory.*—NiO is antiferromagnetic below 525°K and possesses a slightly distorted cubic structure. The twin domain walls in the crystal produced by the magnetic distortion can be removed by an 1800°K anneal followed by a stress along [111] at 300°K. A second variety of domain wall can be removed at 300°K by the application of a magnetic field $H \geq 6000$ oe. The resultant crystal is a single domain antiferromagnet. Torque magnetometer measurements of the anisotropy in the magnetic susceptibility confirm that all of the spins lie in a (111) plane. The anisotropy of the susceptibility in this plane is a function of the magnetic field and of the crystal shape. In a crystal of circular cross section the preferred spin directions possess the expected 3-fold symmetry. The energy loss per cycle for rotation in the (111) plane is about 400 ergs/cm^3 for a representative crystal, and varies with the oxygen content. Provisional values have been obtained for the 3 principal magnetic susceptibilities, one parallel and two perpendicular to the spin axis.

RA3. Crystal Structure and Magnetic Properties of Ferromagnetic Chromium Oxide. W. H. CLOUD, H. S. JARRETT, AND M. S. SADLER, *E. I. du Pont de Nemours and Company.*—Ferromagnetic chromium oxide Cr_xO_2 with $x \sim 1$ has the rutile crystal structure, space group $P^4/mnm(D_{4h}^{14})$. The position of the oxygen atoms is the same as in rutile ($u = 0.31$). The saturation magnetic moment at liquid nitrogen temperature is 1.82 Bohr magnetons per chromium atom. The magnetization *vs* temperature curve shows an apparent Curie temperature at approximately 127°C, but a high-temperature "tail" persists up to 200°C. Superexchange appears to be the principal interaction between chromium atoms at the corners and body center of the unit cell. The geometrical configuration is very close to that of the strong A-B interaction in spinels. The high-temperature "tail" to the magnetization curve suggests that there may also be a direct Cr-Cr interaction along the tetragonal axis. Ferromagnetism is accompanied by high electrical conductivity [3×10^3 (ohm-cm)$^{-1}$] in contrast to much lower electric conductivity [10^{-3} (ohm-cm)$^{-1}$] for antiferromagnetic MnO_2 which has the same crystal structure.

RA4. Magnetization Process in Small Particles of Ferromagnetic Chromium Oxide. F. J. DARNELL AND M. S. SADLER, *E. I. du Pont de Nemours and Company.*—Initial magnetization curves, remanence, coercivity, reversible susceptibility, and rotational hysteresis were measured for the ferromagnetic chromium oxide Cr_xO_2, $x \sim 1$, in aggregates of small particles. Particles ranged from equiaxed with diameter $\sim 10\ \mu$ to acicular with diameter $\sim 0.1\ \mu$ and length/diameter ~ 10. From the field dependence of remanence and from reversible susceptibility, it was found that acicular particles less than $\sim 0.2\ \mu$ in width behaved as single domains with magnetization by rotation only. Larger particles exhibited domain wall motion in addition to rotation. Coercivities of particles studied were dominated by shape anisotropy with little contribution from crystalline anisotropy. Examination of magnetic domain powder patterns on crystals ~ 0.2-mm diam showed coercivities much smaller than observed for the $10\ \mu$ particles and allowed estimation of the uniaxial crystalline anisotropy ($K \sim 3 \times 10^5$ ergs/cm^3).

RA5. Magnetic Properties of $KMnF_3$.* OLOF BECKMAN, A. J. HEEGER, A. M. PORTIS, AND D. T. TEANEY, *University*

of California, Berkeley.—X-ray diffraction, magnetic torsion, and microwave resonance studies have been applied to single crystal $KMnF_3$ in the range from 4.2° to 300°K. The torsion measurements confirm that the material becomes antiferromagnetic below 88.3°K with the magnetization directed along the c axis. A second magnetic transition is observed at 80.5°K in which the magnetization is believed to flop into the transverse plane and cant away from a 110 plane. The x-ray measurements show weak superlattice lines corresponding to four Mn ions per unit cell in accord with the theory of Dzialoshinsky. A remarkable feature of the sample in the range between 80.5° and 88.3°K is the ease with which the magnetization flops into the transverse plane in an applied magnetic field. A reduced critical field may be expected to result from canting. Microwave measurements above 88.3°K give a single isotropic paramagnetic resonance at $g=2.002$ with a half width of 33 oe. Between 80.5° and 88.3°K multiple anisotropic resonances are observed. Below 80.5°K a single isotropic resonance is again observed but shifted down in field by about 450 oe. This line is interpreted as a ferromagnetic resonance of the canted magnetization.

* Supported in part by the U. S. Atomic Energy Commission.

RA6. Piezoelectric and Magnetostrictive Properties of Gallium Iron Oxide Single Crystal Resonators. D. L. WHITE, *Bell Telephone Laboratories.*—Gallium iron oxide,[1] $Ga_{2-x}Fe_xO_3$, $(0.6 \leq x \leq 1.4)$, is a manmade mineral and is believed to be the only known material which is simultaneously piezoelectric and ferromagnetic. Small single crystals in the shape of rectangular prisms were fabricated into resonators which could be driven either piezoelectrically or magnetostrictively. According to the crystal's symmetry class,[2] $C2v$, there are five piezoelectric constants which need not be zero. By exciting the crystals piezoelectrically in various modes of vibration between 0.5 mc and 5 mc, piezoelectric constants were examined. The d_{23} constant is $1.4 \pm 0.3 \times 10^{-8}$ esu which is about twice as large as that of quartz. The d_{12} constant is believed to be of similar magnitude. The other three constants d_{22}, d_{15}, and d_{36}, are smaller and could not be measured. When the crystal was placed in a fixed magnetic field upon which an rf magnetic field was superimposed, resonant modes could be excited magnetostrictively. It was possible to drive the crystals magnetostrictively and detect the resonances piezoelectrically. It was also possible to use a piezoelectric drive and magnetostrictive detection. It had the properties of a gyrator, viz, an antireciprocal transfer matrix.

[1] J. P. Remeika—*Fifth Conference of Magnetism and Magnetic Materials* (American Institute of Electrical Engineers, November 17, 1959, Detroit, Michigan).
[2] E. A. Wood, Acta Cryst. (to be published).

RA7. Magnetic Susceptibilities of $Co(C_2H_3O_2)_2 \cdot 4H_2O$, $Ni(C_2H_3O_2)_2 \cdot 4H_2O$, and $Mn(C_2H_3O_2)_2 \cdot 4H_2O$ at Low Temperatures.* R. B. FLIPPEN AND S. A. FRIEDBERG, *Carnegie Institute of Technology.*—The magnetic susceptibilities of powdered $Co(C_2H_3O_2)_2 \cdot 4H_2O$ and $Ni(C_2H_3O_2)_2 \cdot 4H_2O$ and of both powdered and single crystal $Mn(C_2H_3O_2)_2 \cdot 4H_2O$ have been measured in the liquid hydrogen and helium ranges by an ac bridge method. While all of these materials have monoclinic structures only the nickel and cobalt salts are isomorphous. All three salts exhibit Curie-Weiss behavior between 14° and 20.2°K; for $Co(C_2H_3O_2)_2 \cdot 4H_2O$ this continues down to 1.3°K. Cooling this salt by adiabatic demagnetization reveals a sharp susceptibility peak near 0.6°K. The susceptibility of the nickel salt deviates from a Curie-Weiss law below 4.2°K without evidence of cooperative behavior. Significant cooling was not observed upon demagnetization from a field of ~5000 gauss at 1.3°K. Powdered $Mn(C_2H_3O_2)_2 \cdot 4H_2O$ exhibits a very large susceptibility peak at 3.18°K, the same temperature at which a lambda anomaly has been found in preliminary specific heat measurements. As the temperature is lowered through this point single crystal measurements in the a, b, and c directions show: χ_a passing through a very sharp peak, χ_b going through a less pronounced peak, and χ_c changing only slightly before assuming a nearly constant value. These susceptibilities are strongly influenced by weak external fields. Hysteresis is found in the a direction.

* Work supported by the Office of Naval Research, the National Science Foundation, and the Alfred P. Sloan Foundation.

RA8. Crystalline Anisotropy of Mn_2Sb. H. S. JARRETT AND F. J. DARNELL, *E. I. du Pont de Nemours and Company.*—The crystalline anisotropy constants of Mn_2Sb have been determined in the temperature range −65° to +85°C. Torque curves were obtained on a rotating torque magnetometer using a single crystal disk cut to contain an a,c plane of the tetragonal structure. K_1 and K_2 in the energy expression $E_A = K_1 \sin^2\phi + K_2 \sin^4\phi$ were found by a least squares fit of the derived torque to the experimental data. K_1 varies from -45×10^4 ergs/cm³ at −65°C to $+58 \times 10^4$ at 85°C, with $K_1 = 0$ at −21°C. K_2 is positive over the measured range, rising from 5×10^4 at −65°C to a maximum of 17×10^4 at 50°C and then falling at higher temperatures. The compensation point at which $K_1 + K_2 = 0$ is −26°C, in fair agreement with the work of Guillaud.[1] At temperatures above −21°C the Mn spins lie along the c axis, while below −32°C the spins lie perpendicular to the c axis. In the range −31° to −32°C, where $0 < -K_1 < 2K_2$, the spin direction should change continuously from the c axis to the basal plane. Neutron diffraction studies[2] support this conclusion.

[1] C. Guillaud, Thesis, Strasbourg 1943; C. Guillaud, R. Bertrand, and R. Vautier, Compt. rend. **228**, 1403–1405 (1949).
[2] M. K. Wilkinson, N. S. Gingrich, and C. G. Shull, J. Phys. Chem. Solids **2**, 289–300 (1957).

RA9. Application of Neél-Taniguchi Theory to Irradiated Magnetic Materials. A. I. SCHINDLER AND E. I. SALKOVITZ, *U. S. Naval Research Laboratory.*—Experiments have been performed to determine the basis of neutron irradiation effects on the magnetic properties of iron-nickel alloys. Two samples each of a variety of compositions have been irradiated at room temperature, with and without applied dc magnetic field, in the Brookhaven reactor. All the results can be explained within the framework of the Neél-Taniguchi theory relating magnetic properties to directional ordering. If the samples are irradiated for a two week period, short range directional order results, and the resulting hysteresis loops clearly show the domain distribution present during the irradiation. For samples irradiated with a saturating dc field present, the domains are aligned, and rectangular hysteresis loops result. If no field is present during the irradiation, constricted hysteresis loops result but the amount of the constriction depends on the amount of domain alignment prior to irradiation. The differences are most evident for rectangular hysteresis loop materials. If longer times of irradiation are employed long range order appears to result which impedes the directional short range ordering and unconstricted but modified loops result. Some materials have been found which exhibit constricted hysteresis loops because of irradiation in zero magnetic field, but undergo only minor changes if irradiated in a saturating dc magnetic field.

WEDNESDAY MORNING AT 9:30

WSU Community Arts Auditorium

(D. WILSDORF presiding)

Mostly Dislocations

S1. Mechanism of Formation of Helical Dislocations in Silicon.* W. C. DASH, *General Electric Research Laboratory.*—Screw dislocations climb to form helices when gold is diffused into silicon crystals at about 1200°C.[1] The following experiments have been performed to elucidate the mechanism of formation of the helices. From localized surface damage, a small number of dislocation loops are moved into an otherwise dislocation-free crystal by an applied stress at 900°C. The geometry of deformation is such that the screw portions of the loops are left-handed. Upon diffusion of gold only right-handed helices are formed. This leads to the conclusion that in effect a vacancy deficiency produces the climb. The present investigation has shown that only those screw dislocations which are substantially free from impurities climb to form helices. In other cases either distorted helices form, or there may be no climb of the screw dislocations. In such specimens randomly distributed prismatic loops are frequently found.

* Supported by Wright Air Development Center.
[1] W. C. Dash, Phys. Rev. Letters 1, 400 (1958).

S2. Etch Pit Studies of ZnS Crystals. S. J. CZYZAK, *University of Detroit,* AND D. C. REYNOLDS, *Aeronautical Research Laboratory.*—Etch pits were formed on ZnS crystals by immersing the crystals in boiling concentrated HNO_3 acid for a period from two to five minutes. We find that etch pits form on the 0001 face and show a difference in the etching characteristics between the 0001 and $000\bar{1}$ faces as observed in InSb[1] and CdS[2]. On the 0001 face distorted hexagonal etch pits form while on the $000\bar{1}$ face a mottled surface is observed. Assuming that the Zn atoms carry a positive charge and the sulphur atoms a negative one, it has been determined from the sign of the piezoelectric voltage that the hexagonal shaped etch pits form on that face of the crystal on which the sulphur is exposed. Dislocation densities have been determined from the etch pits for a number of crystals, and it has been observed that the density varies over a range anywhere from 10^4/cm to 10^7/cm. X-ray diffraction measurements show that in these crystals both the wurtzite and sphalerite phases are present; however, the predominant phase appears to be wurtzite.

[1] M. C. Lavine, A. J. Rosenberg, and H. C. Gates, J. Appl. Phys. **29**, 1131 (1958).
[2] D. C. Reynolds and S. J. Czyzak, J. Appl. Phys. (to be published).

S3. Charged Dislocations in Lithium Fluoride.* R. L. SPROULL, *European Research Associates, Brussels.*—The application of strong electrostatic fields to bent LiF crystals at room temperature produced small motions (0.1 to 6 A) of the bends which were analyzed in terms of even functions of field (electrostriction) and odd functions (thought to be the motion of positively charged dislocations) which increased more rapidly than linearly with increasing field. Dislocations should be charged[1] in an ionic crystal if the free energies of formation of positive and negative ion vacancies are unequal. From the data and estimates of the mole fraction of + ion vacancies (10^{-7} to 10^{-5}), the charge density on the dislocation core (2×10^{-3} to 9×10^{-5} esu/cm, positive) and the electrostatic contribution to the critical shear stress (5000 to 50 g/cm²) were calculated. These values tend to confirm the suggestion[1] that electrostatic forces between charged dislocations and their surrounding charge clouds are a substantial part of the critical shear stress. The data indicate that the free energy of formation of a positive ion vacancy in LiF may be 0.3 ev, but this very small value may be in error because of precipitation of divalent impurities or their association with vacancies.

* Supported by the Union Carbide Company.
[1] Eshelby, Newey, Platt, and Lidiard, Phil. Mag. **3**, 75 (1958).

S4. Etch Pits and Dislocations in Pure Copper. F. W. YOUNG, JR., *Oak Ridge National Laboratory.**—Methods will be described for revealing dislocations as etch pits on the (111), (100), and (110) faces of 99.999% copper. By altering the composition of the etch solutions pits of conical or crystallographic shapes can be formed. Both grown-in and newly-formed dislocations are etched by these techniques. Some of the conditions necessary for the formation of pits at dislocations in copper will be discussed.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

S5. Theory of Dislocation Climb.* ROBB THOMSON, *University of Illinois.*—A formalism has been constructed which describes the kinetic theory of the jog production and subsequent climb of an edge dislocation. Climb is described in terms of the nucleation of vacancy and interstitial aggregates on the dislocation. When detailed balance is imposed on the system, the density of jogs in equilibrium is shown to be a simple Boltzmann factor. In addition to equilibrium, it is also possible to obtain solutions in the case of steady state climb, where the rate of climb depends upon the vacancy mobilities and jog energies in a sensitive way. Qualitatively, if the mobility is high, vacancies incident upon the line easily find jogs and the climb rate is high. The climb rate is also high if the jog energy is low and the nucleation of jogs is easy.

S6. Evidence for Dislocation Interactions in Rolling Friction. LAWRENCE D. DYER, *General Motors Research Laboratories.*—Both rolling friction and track width were found to vary with crystallographic direction when a sapphire ball was rolled in various directions on the cube face of a copper crystal. For a ¼-inch ball under a hundred-gram load, the rolling resistance was found to increase 18% in changing from the ⟨100⟩ direction to the ⟨110⟩ direction while the track width decreased 10%. The topography of the derfomed areas was studied by optical and interference microscopy and microhardness measurements were made in and around the tracks. These studies aided in developing an explanation for the observed anisotropies. The track width variation may be explained by a detailed consideration of the topography ahead of the advancing ball. The variation in rolling resistance may be explained by the formation of Lomer-Cottrell sessile dislocations under the (100)⟨110⟩ tracks and the difficulty of pushing dislocations through the substrate that contains them.

S7. High-Angle Tilt Boundary. JAMES C. M. LI, *United States Steel Corporation.*—The dislocation model of a low-angle substructure boundary is extended to the case of a high-angle symmetric tilt boundary. By using the approximation that the stress field of the boundary is equal to the sum of those of the individual dislocations in their isolated states in an infinite medium, with proper corrections at the cores of the dislocations, the following results are obtained: (1) the Chalmers dislocation model changes into that of a boundary where dislocations of single and double Burgers vectors are alter-

nately arranged, (2) the stress field of a high-angle boundary is such that the boundary can be fractured without a long pile-up of dislocations, (3) the porosity of the boundary becomes proportional to the square of the sine of the angle at the high-angle side, (4) the energy of the boundary has a minimum at the angle of largest misfit, and (5) the structure of a boundary may not be a continuous function of angle and other variables. But when it is, the boundary becomes more or less "amorphous" at the high-angle side due to thermal agitation. This model predicts a continuous transition between the "transition lattice" type and the "amorphous" type of boundaries and a discontinuous transition between two "transition lattice" type boundaries.

S8. Fracture of Brittle Solids. J. J. GILVARRY AND B. H. BERGSTROM, *Allis-Chalmers Manufacturing Company.*—The theory of probability is used to calculate the distribution function for fragment sizes in single fracture. On the model adopted, fracture planes are initiated at Griffith flaws in the volume, in fracture surfaces, and in edges formed by intersection of fracture surfaces. If the flaws of each type are independently distributed at random, individually and collectively, the distribution function is of Poisson form. Comparison with experimental distributions implies that edge flaws play the preponderant role in fracture. The idealization of collective randomness results in a distribution function yielding divergent integrals for the total number, edge length, and surface of the fragments. Further, the calculated distribution function fails to agree with experiment at sizes near that of the largest fragment, and at roughly a few microns. These anomalies are explained by neglect of flaw depletion. This effect is taken into account by an analogy with the theory of radioactive decay. Solution of a set of differential equations yields a distribution function agreeing well with experiment at all fragment sizes; the total number, edge length and surface of the fragments are represented by convergent integrals.

S9. Oxidation and Reduction Products on Iron Whisker Surfaces. J. V. LAUKONIS, *General Motors Research Laboratories,* AND R. V. COLEMAN,* *University of Illinois.*—Oxide products and the surfaces which are formed when such products are chemically reduced have been studied on single crystal iron whiskers. Previous results[1] on oxidation products will be extended. Hydrogen reduction of these oxide products has been observed to produce terraced hill-and-valley structures which characterize the orientation of the iron substrate. Correlations between the oxide morphology and the topography of the iron surfaces which are present after the reduction will be discussed. The orientation dependence of both oxidation and reduction processes will be illustrated on polycrystalline whisker surfaces which result when the α-iron crystals are heated above the transition temperature (910°C).

* Supported in part by the U. S. Atomic Energy Commission.
[1] J. V. Laukonis and R. V. Coleman, J. Appl. Phys. **30**, 1364 (1959).

S10. Tensile Strength of Pyrolytic Graphite Up to 2750°C.* H. E. MARTENS AND L. D. JAFFE, *California Institute of Technology.*—The ultimate tensile strength of a pyrolytic graphite was measured from room temperature to 2750°C. The material tested[1] was deposited at 2100°C from a hydrocarbon gas and had a density of 2.20 gm/cc. The strength parallel to the basal planes of the hexagonal lattice was found to be approximately 18 000 psi (1.3×10^9 dyne/cm^2) at 25°C, 30 000 psi (2.1×10^9 dyne/cm^2) at 2500°C, and 50 000 psi (3.5×10^9 dyne/cm^2) at 2750°C. This is considerably higher than the strength of normal synthetic graphites made from petroleum coke and coal tar pitch, where high values are 3000 psi (2.1×10^8 dyne/cm^2), 6000 psi (4.2×10^8 dyne/cm^2), and 4000 psi (2.8×10^8 dyne/cm^2), respectively, at the same temperatures.[2] The data are considered preliminary as they were obtained from a limited number of tests and with some experimental difficulties.

* This work was supported by the U. S. National Aeronautics and Space Administration.
[1] Supplied by U. S. Navy, Bureau of Naval Weapons.
[2] H. E. Martens, L. D. Jaffe, and J. E. Jepson, *Proceedings of the Third Conference on Carbon* (Pergamon Press, London, 1959), p. 529.

S11. Determination of Surface Structure Using Ultra-High Vacuum Replication.* L. BACHMANN,† W. ORR, T. RHODIN, AND B. SIEGEL, *Cornell University.*—Electron microscopy has been applied to the problem of characterizing the distribution of preferred sites for nucleation and growth on clean surfaces of evaporated films of magnesium metal. The films were deposited, platinum-shadowed, and carbon-backed in the same system under ultra-high vacuum conditions to minimize surface contamination and to improve the fidelity of surface replication. Upon examination of both clean and oxidized films in the electron microscope the distribution of the platinum deposit was observed to be markedly influenced by the high vacuum conditions used in the replication procedure. The particle size and separation of the platinum grains and their distribution with relation to the substrate also indicated an enhanced surface mobility on cleaved mica and an apparent reaction on magnesium. These observations may have bearing on both the surface properties of metal deposits and on the development of high resolution replication techniques.

* Work supported jointly by the Air Force Office of Scientific Research and the Office of Naval Research.
† Now at University of Innsbruck, Austria.

WEDNESDAY MORNING AT 9:30

Engineering Society

(W. P. SLICHTER presiding)

High-Polymer Physics III

Invited Papers

T1. Bulk Crystallization and Morphology of High Polymers. H. D. KEITH, *American Viscose Corporation.* (50 min.)

T2. Theory of Chain Folding of Polymer Molecules in Dilute Solution. J. D. HOFFMAN, *National Bureau of Standards.* (40 min.)

T3. Thermodynamic Stability of Single Crystals of Linear Polymers. A. PETERLIN, *Institute Jozef Stefan, Ljubljana, Yugoslavia.* (30 min.)

WEDNESDAY AFTERNOON AT 2:00

Engineering Society

(H. LEADERMAN presiding)

High-Polymer Physics IV

U1. Effect of Intrachain and Interchain Interactions on the Structures of Crystalline Regions in Linear Polymers. MAURICE L. HUGGINS, *Stanford Research Institute.*—To explain (1) long x-ray spacings in crystalline polyethylene, (2) regular shapes and dimensions of molecules of polyethylene in dilute solution, and (3) regular steps in the surface structures of polyethylene crystals from dilute solution, it is proposed that (1) intrachain forces produce slight departures from a planar zigzag structure of the carbon chain, (2) intrachain and/or interchain forces make these departures uniformly alike within each chain, giving it a twisted ribbon structure, and (3) when the twists reach a limiting value, depending primarily on interchain forces, a sudden alteration in structure occurs. Similar ideas are applicable to polymer structures in which intramolecular forces tend to produce a molecular structure, which departs slightly from one with a helical axis of simple multiplicity. To account for the large-spacing data from fibrous proteins such as keratin and collagen, it is proposed that corresponding points in neighboring molecular chains are shifted parallel to their molecular axes, spirally or otherwise in order to (1) surround like groups in a like manner, and (2) minimize the energy of intramolecular interactions.

U2. Pyramidal Single Crystals of Polyethylene. WALTER D. NIEGISCH AND PAUL R. SWAN, *Research Center, Union Carbide Plastics Company.*—One of the most intriguing and puzzling phenomena to come to light in the field of polymer structure in recent years has been the suggestion that polymers crystallize in the folded chain configuration. While studying this model, some unusual diffraction effects and other evidence were obtained which resulted in postulating the existence of hollow pyramidal single crystals of polyethylene by Niegisch,[1,2] and recently corroborated by Bassett, Frank, and Keller.[3] A mechanism of formation of the pyramidal configuration deduced from unpublished data will be presented, which suggests the manner in which possible steric hindrance may be overcome at the bends of the folding polymer molecule. Application of the pyramidal model to truncated crystals will be discussed as well as the reasons for considering this crystal form to be of importance.

[1] W. D. Niegisch, "The relation of single crystals to polyethylene spherulite formation," presented at the 17th Annual Meeting of the Electron Microscope Society of America, Columbus, Ohio (September 11, 1959).
[2] W. D. Niegisch, J. Polymer Sci. **40**, 263 (1959).
[3] D. C. Bassett, F. C. Frank, and A. Keller, Nature **184**, 810 (1959).

U3. On the Crystallization of Polyethylene from Dilute Solutions. F. KHOURY AND F. J. PADDEN, JR., *American Viscose Corporation.*—The morphology of aggregates formed on crystallizing polyethylene from dilute (0.0005%–0.5%, w/v) solutions in xylene has been studied using phase and electron microscopy. This work has essentially been confined to the different aggregates formed when (a) polymer solutions at 140°C were rapidly cooled to 85°C and maintained at that temperature for a few days and (b) polymer solutions were allowed to cool slowly from 140°C to room temperature. The results are presented as a preliminary attempt to determine the processes which lead to the crystallization of polyethylene in forms other than stepped double-pyramids. In particular, the contribution of twinning to a change from the single lozenge shaped crystal "growth habit" will be indicated. Further, two different ways are described in which growth steps form through screw dislocation mechanisms near the external edges of single platelets which protrude from the complex central regions (too thick to be resolved) of aggregates formed in (a). The effect of twinning on the crystal orientation in these steps is also shown. The surface structure of aggregates formed in (b), as determined by a replicating method will be briefly discussed.

U4. Defects in Polyethylene Crystals. W. P. SLICHTER, *Bell Telephone Laboratories.*—Recent observations by Keller, Stuart, Peterlin, and others have revised concepts of crystalline structures in polymers and have emphasized the role of lattice defects in the morphology. Some factors affecting the nature of defects are reported here, based on observations from nuclear magnetic resonance spectroscopy and x-ray diffraction. Samples of Phillips-type polyethylene were examined, after crystallization from xylene or perchloroethylene solution at varying temperatures and concentrations. Molecular segmental mobility, ascribed to the presence of lattice defects, becomes more abundant at room temperature as the crystallization temperature is lowered or as the solution concentration is increased. Solution-grown samples are low in segmental mobility compared with those crystallized from the melt. Segmental mobility in solution-grown samples, measured at room temperature, is independent of annealing conditions until the annealing temperature exceeds about 100°C. The mobility then becomes irreversibly greater, and as the annealing temperature is raised the motion is reminiscent of that in samples crystallized from the melt. Linear polyethylenes crystallized at elevated pressure and temperature, found by Matsuoka to exhibit abnormally high densities, nevertheless show a sizable amount of segmental mobility, suggesting that such crystallization produces numerous defects.

U5. Properties of Polyethylene Crystallized at High Pressure. SHIRO MATSUOKA, *Bell Telephone Laboratories, Inc.* (Introduced by W. P. Slichter).—It has been found previously[1] that crystallization may be induced in a polyethylene melt by pressure. The crystallization isotherms thus obtained are in general not completely superimposable along the logarithmic time scale. The final degree of crystallinity is thus influenced by the conditions of crystallization. The kinetics of crystallization in turn seem to be influenced by the extent of bulk relaxation prior to crystallization. By crystallizing Phillips-type polyethylene under various temperatures and pressures, specimens with density varying from 0.955 to 0.081 were obtained.

[1] To be published in J. Polymer Sci.; also S. Matsuoka and B. Maxwell, J. Polymer Sci. **32**, 131 (1958); and W. Park and R. B. Richards, Trans. Faraday Soc. **45**, 203 (1949).

U6. Photographic Low Angle Light Scattering Studies of Crystalline Polymers.* M. B. RHODES† AND R. S. STEIN, *University of Massachusetts.*—Light scattering patterns are obtained from films of polyethylene and polyethylene oxide by passing a well-collimated light beam normally through the film. The patterns are recorded photographically. They are obtained as a function of polarization of the incident and scattered light beam, sample history, temperature, and orientation. It is possible to measure spherulite size, anisotropy of refractive index, refractive index difference between the

spherulite and its surroundings, distortion, and internal structure. Most of the low angle scattering at room temperature results from the anisotropy of spherulite refractive index where the tangential refractive index is greater than the radial. Periodicity in orientation of the constituent crystals gives rise to scattering maxima. By using a very small light beam with large spherulites of polyethylene oxide, it is possible to obtain scattering patterns from portions of spherulites and thus learn of the arrangement of their constituent parts. The results are consistant with a model consisting of rod or plate-like structures with their greatest dimension oriented radially and their highest refractive index oriented tangentially.

* Supported in part by a contract with the Office of Naval Research and in part by grants from the National Science Foundation, the Plax Corporation and assistance from the Monsanto Chemical Company.
† National Science Foundation Faculty Research Fellow.

U7. The Scattering of Light by Spherulites Having Radial Periodicity in Orientation.* R. S. STEIN, A. PLAZA, AND P. R. WILSON, *University of Massachusetts.*—Keller and Price have proposed that the ringed structure observed in polyethylene spherulites results from a variation of the orientation of their constituent crystals with distance from the center of the spherulite. The *b* axis of the crystals is oriented radially and the *a* and *c* axes rotate about the *b* through an angle proportional to the distance from the center, A theory for the scattering of radiation from an isolated spherulite having uniform density, but radially varying orientation is developed. The equations contain two types of terms; one of which depends upon the difference between the average refractive index of the spherulite and that of the surroundings, and the second depends upon the difference between the principal refractive indices of the crystals. The first term is similar to the scattering from a uniform sphere, while the second possesses a maximum at a position related to the inter-ring spacing, *d*, by a Bragg type equation, $\lambda = 2d \sin\theta$. The first term becomes less important in a system consisting of closely packed spherulites. The effects of polarization of the light are predicted. Experimental light scattering data are presented.

* Supported in part by a contract with the Office of Naval Research and in part by grants from the National Science Foundation and the Plax Corporation and assistance from the Monsanto Chemical Company.

U8. Measurement of Polymer Film Clarity. Z. W. WILCHINSKY, *Esso Research and Engineering Company.*—Clarity, related to loss of resolution when viewing objects through a sample, was measured by light scattering and visual methods. The minimum angle of resolution (resolving power), attributable to the polymer film was very nearly equal to the width of the scattering curve at half its maximum intensity. For samples of high clarity, the light scattering instrument,[1] having a resolving power of 2 min of arc, was the limiting factor. By applying a correction for the instrument, measurements of films were carried down to one minute. The visual method, in its simplest form, is limited by the resolving power of the eye (about 2 min), but this limitation can be removed by using a telescope in viewing a test object through a film. Satisfactory agreement between the light scattering and visual methods was obtained for minimum angles of resolution down to one minute of arc. Extruded films showed directional effects; up to severalfold greater scattering was observed transverse to the direction of extrusion than parallel to it.

[1] Model III Scattermaster, Manufacturers Engineering and Equipment Corporation, Hatboro, Pennsylvania.

U9. Morphology of an Acetal Resin. P. H. GEIL, *E. I. Du Pont de Nemours and Co.*—Lamellae are basic structural elements of the acetal resin, polyoxymethylene. Lamellae similar to those observed after precipitation of polymer single crystals from solution are found both in the interior and on the surface of samples crystallized from the melt. Both the thickness and the melting point of these lamellae depend on the temperature of crystallization. When crystallized from the melt, lamellae are organized into spherulites or hedrites. The latter are hexagonal structures several microns thick. The lamellae, which consist of folded polyoxymethylene molecules, originate at screw dislocations, at the centers of both spherulites and hedrites as well as on the periphery of growing spherulites.

U10. Morphology of Polymer Single Crystals. D. H. RENEKER AND P. H. GEIL, *E. I. Du Pont de Nemours and Co.*—Polyethylene crystals grow from solution in the form of hollow pyramids as well as flat lamellae. The pyramid faces consist of 100 A thick lamellae inclined at an angle of about 17° to the base plane. In the flat crystals the folds in the molecule pack so that adjacent folds are tangent to a (001) plane, that is a plane normal to the molecular axis. In the pyramidal crystals, the packing is such that the folds are all tangent to {112} planes. Polymer crystals grow in the direction of the molecular axis through the formation of spiral growths around screw dislocations in the underlying lamellae. Several types of sources for screw dislocations in polyethylene and polyoxymethylene lamella have been identified.

WEDNESDAY AFTERNOON AT 2:15

Lecture Hall, Institute of Arts

(W. SHOCKLEY presiding)

Transport Properties: Silicon and Germanium, II

V1. Variational Treatment of Warm Electrons in Nonpolar Crystals. I. ADAWI, *RCA Laboratories.*—Studies of deviations from Ohm's law in nonpolar crystals are extended, using the variational method, over a wider range of temperature than previously reported,[1] with reference to *n*-type Ge. Two effective masses are assumed. Included in the scattering are both acoustical and optical phonons, and ionized impurities. The ionized impurity effect[2] is important here too. It is proven that the relative importance of optical phonon scattering is maximum at a temperature which corresponds, approximately, to the optical phonon energy. The low temperature limit is, of course, that of acoustical phonons alone, and that of high temperature (if realizable in certain situations) is the same except for a factor which is of the order of unity. Finally, the convergence of the variational method is established in a limiting case using as a representation a set of polynomials, which are orthonormal with respect to the collision operator.

[1] I. Adawi, Bull. Am. Phys. Soc. Ser. II, **4**, 129 (1959); Phys. Rev. **115**, 1152 (1959).
[2] I. Adawi, Phys. Rev. **112**, 1567 (1958).

V2. Electron Distribution Function in *n*-Germanium. THOMAS N. MORGAN, *IBM.*—Solutions of a Boltzman equation appropriate for electrons in germanium have been computed on an IBM 704 for the case of weak applied electric fields (warm electron phenomena). Elastic scattering of electrons by ionized impurities and inelastic scattering by both acoustic and optical phonon modes have been included. The method of solution developed minimizes an appropriate functional quadratic in the distribution function and assures a unique solution. The transport integrals for mobility, Hall constant, and intervalley carrier transfer are valid to order E^2 for a weak applied electric field, E. A comparison with experimental data will be given.

V3. Anisotropy of Drift Velocity vs Electric Field in *n*-Type Germanium. MARSHALL I. NATHAN, *IBM Research Laboratory, Poughkeepsie.*—Current density vs electric field has been measured up to 10 000 v/cm in *n*-type germanium at 77° and 297°K for the field in the (100), (110) and (111) crystallographic directions. At 77°K for 1000 v/cm the drift velocity in the (100) direction is 60% greater than in the (111) direction. By 10 000 v/cm, this difference (the longitudinal anisotropy) has decreased from its maximum value at 1000 v/cm to 15%. The (110) curve lies between the other two. This anisotropy is explainable in terms of the effective mass anisotropy and population changes of the conduction band valleys oriented differently with respect to the field. The drift velocity of a single valley and the change of inter-valley scattering rate as a function of field are deduced. The latter increases by a factor of 20 over the range of applied field. The transverse anisotropy[1] is also deduced. Reasonable agreement is found with measurements performed in this laboratory, in which geometric effects due to current spread into the side arms are eliminated. The 297°K data shows negligible longitudinal anisotropy. This cannot be explained with the analysis applied to the 77°K data.

[1] Sasaki, Shibuya, and Mizuguchi, J. Phys. Soc. (Japan) **13**, 456 (1958).

V4. Temperature Dependence of Mobility in *p*-Type Germanium ($T<77$°K).* DALE M. BROWN AND RALPH BRAY, *Purdue University.*—Analysis[1] of the $T^{-2.3}$ mobility dependence in *p*-type Ge in the range $100°K \leqslant T \leqslant 300°K$ on the basis of acoustical and optical mode scattering predicts complete absence of the latter at $T \leqslant 70°K$. Therefore, the mobility in relatively pure samples (lattice mobility dominant) has been studied to determine whether a $T^{-\frac{3}{2}}$ relationship, characteristic of *simple acoustical mode scattering*, exists for lattice mobility at low temperature. In the range $15°K \leqslant T \leqslant 70°K$, excellent fit to data could be obtained with calculations based on a lattice mobility $\mu^L = 580\,000(T/15°K)^{-\frac{3}{2}}$ cm²/v sec, and impurity mobility μ^I given by Brooks-Herring formula. On the basis of strong field approximation, the Hall mobility at 7000 gauss was taken equal to the conductivity mobility. The analysis was based on a spherical, doubly degenerate band structure, taken into account to the extent of assuming $\mu_l{}^L/\mu_h{}^L = m_h{}^*/m_l{}^* = 0.35/0.043$, independent of temperature. For impurity scattering, intraband transitions only, were assumed. By utilizing the above value of μ^L, an empirical test of the range of utility of the Brooks-Herring formula was made down to 7°K on a sample with $N_A - N_D = 1.25 \times 10^{13}$/cm³, and at 77°K for samples with impurity concentrations up to 5×10^{16}/cm³.

* Supported by Signal Corps Contract.
[1] E. M. Conwell, J. Phys. Chem. Solids **8**, 234 (1959); Sylvania Tech. **12**, 30 (1959).

V5. Acoustical Phonon Scattering of Hot Carriers in *p*-Type Germanium. RALPH BRAY AND DALE M. BROWN, *Purdue University.*—The primary purpose of this work was to test hot carrier mobility theory for the simple, Shockley case of interaction of carriers with acoustical phonons of energy $\hbar\omega < kT_{\text{lattice}}$. Mobility measurements were made on a relatively pure *p*-type germanium sample ($N_A + N_D = 1.65 \times 10^{13}$/cm³) at 3½°K, where (1) lattice scattering is purely by acoustical phonons (see preceding abstract), (2) impurity "exhaustion" still prevails, and (3) carrier-carrier energy exchange is estimated to be sufficiently strong to establish Maxwell-Boltzmann energy distribution. The theory, after simple modifications to take account of impurity scattering and the double valence band structure, gives excellent agreement with experiment even beyond the range of validity, to $E \leqslant 100$ v/cm, $T_{\text{carriers}} \leqslant 500$°K). Also, surprisingly, at higher fields ($400 \leqslant E \leqslant 6000$ v/cm) a theoretical expression (Stratton[1]) based on acoustical phonon interactions in the limiting case $\hbar\omega \gg kT_{\text{lattice}}$ (phonon emission) fits very well to the data. Inclusion in the theory of expected optical phonon emission makes the agreement appreciably poorer. However, the effect of modifications in band structure for high energy carriers has been neglected. At higher lattice temperatures (77°K and 195°K), the pure acoustical phonon theory gives progressively poorer agreement with experiment.

* Supported by Signal Corps Contract.
[1] R. Stratton, Proc. Royal Soc. (London) A242, 355 (1957).

V6. Effect of Strain on the Low Temperature Electrical Conductivity of Germanium. JOHN J. HALL, *Columbia University* and *IBM Watson Laboratory*, AND S. H. KOENIG, *IBM Watson Laboratory.*—The low and high field electrical conductivity of high purity *n*-type germanium has been measured at liquid He temperature as a function of uniaxial compressive stress in the [111] direction. The strains attained were sufficient to lower the energy of one conduction band valley with respect to the remaining three so that essentially all of the free carriers were in this valley. In this limit, the low temperature linear conductivity was observed to become stress independent, or saturate, as expected. For current in the [111] direction, the saturation value of the linear conductivity was greater than that for no applied stress; this effect is presumably associated with a decrease in the effective activation energy (disappearance of the "chemical shift") as discussed by Price.[1] The high field conductivity, however, decreased in the saturation limit and the breakdown field[2] became greater; this effect will be discussed in terms of a simple Shockley-type model.[3]

[1] P. J. Price, Phys. Rev. **104**, 1223 (1956).
[2] See, for example, S. H. Koenig and G. R. Gunther-Mohr, J. Phys. Chem. Solids **2**, 268 (1957).
[3] W. Shockley, Bell System Tech. J. **30**, 990 (1951).

V7. Electric Field Dependence of the Impact Ionization Probability of Group V Donors in *n*-Type Germanium.* S. C. BROWN AND G. ASCARELLI,† *MIT.*—The time interval elapsed between the instant a "breakdown" field is applied to a germanium sample and the instant the electron density reaches an arbitrary preset value is measured as a function of the applied dc field. It is shown that this time interval is proportional to the time constant describing the rate of change of the electron density. It is found that the time constant varied proportionally to $E^{-1}(E-E_B)^{-1}$, where E_B is the value of the breakdown field corresponding to a very long time interval (of the order of milliseconds). Under some reasonable simplifying assumptions, it is shown that the probability of impact ionization should be proportional to $E(E-E_B)$.

* This work was supported in part by the U. S. Army Signal Corps, the U. S. Air Force Office of Scientific Research, Air Research and Development Command, and the U. S. Office of Naval Research.
† Present address: University of Illinois, Urbana, Illinois.

V8. Majority Carrier Recombination in *n*-Type Germanium.* G. ASCARELLI AND S. C. BROWN, *MIT.*—Continuing our study on the recombination of electrons and donors in germanium we studied the recombination with arsenic

donors. The temperature dependence of the recombination cross section is approximatively $T^{-2.5}$ for both donors but the magnitude is decreased by a factor about 10 compared with the case of Sb. By taking our measurements on the same sample used by Koenig[1] for previous measurements, a discrepancy of a factor 3 in the experimental time constant was found. This discrepancy is attributed to Joule heating produced in Koenig's measurements. The time constant measured by Koenig at the lowest temperature (4.5°K) can be calculated from known data according to the usual theory of thermal conductivity. The fact that our measurements of the density decay time constant falls on a tangent to the high temperature end of the logarithm of Koenig's data (corresponding to a $T^{-\frac{1}{2}}$ dependence of the cross section) gives a further indication confirming our interpretation of Koenig's results.

* This work was supported in part by the U. S. Army Signal Corps, the U. S. Air Force Office of Scientific Research Air Research and Development Command, the U. S. Navy Office of Naval Research.
[1] S. H. Koenig, Phys. Rev. 110, 988 (1958).

V9. High-Frequency Conductivity and Dielectric Constant vs Electric Field Intensity in Germanium.* E. M. CONWELL, *Sylvania Research Laboratories.*—According to the simple treatment of ac conduction which assumes all carriers have the same relaxation time τ, the ac conductivity σ is less than the dc value by the factor $(1+\omega^2\tau^2)^{-1}$, and the dielectric constant of the material is given by $\epsilon=\epsilon_L-4\pi\sigma\tau$, there ϵ_L is the lattice contribution. Calculations for n-type Ge indicate that at 78° for samples of 0.5 ohm cm resistivity or less the free carrier contribution to ϵ is comparable to or larger than the lattice contribution up to frequencies as high as 70 kMc. Application of a high electric field to an n-type Ge sample is known to decrease τ. Thus, if ϵ were measured as a function of electric field intensity for a sample with appreciable free carrier contribution, it should be found to increase with increasing field, returning to the value ϵ_L in the limit of very high fields. The dielectric constant data could in principle be used, in conjunction with mobility data, to determine the mass of the hot carriers. Preliminary results (see next abstract) for an 0.67-ohm cm n-type Ge sample are in qualitative agreement with the theory given above.

* Work supported in part by the U. S. Air Force.

V10. Measurement of the Complex Conductivity of Germanium as a Function of Electric Field Intensity at 69.5 kMc* VERNON J. FOWLER, *Sylvania Research Laboratories* (sponsored by E. M. Conwell).—Standing-wave measurements were made at 300° and 78°K to determine the small-signal complex conductivity of n- and p-type Ge at 69.5 kMc as a function of the magnitude of a bias field, applied as microsecond pulses ranging from zero to 6 kv/cm. The microwave signal was obtained from a pulsed magnetron synchronized with the bias pulses. Uniform field conditions were obtained by using thin wire samples mounted vertically in the center of a waveguide short-circuited one-quarter guide wavelength beyond the sample. To avoid injection of minority carriers into the thin wire sample during the signal pulse, the injecting contact was made through a thick portion of the same Ge crystal with the transit time of minority carriers much longer than the signal pulse duration. Green's function for a line current in a waveguide was set up and used to determine the field produced by the currents in the sample and in its image in the short-circuited end of the waveguide. This enabled the calculation of small-signal conductivity and dielectric constant to be made from the standing wave data. Numerical integration of these data yielded instantaneous conduction current density and electric displacement as functions of the electric intensity; these were compared with theoretical predictions.[1]

* Work supported by the U. S. Air Force.
[1] Preceding abstract.

V11. High-Frequency Current Noise in p-Type Germanium at 4.2°K. HENRY SHENKER, *U. S. Naval Research Laboratory.*—In the liquid helium temperature range, germanium exhibits a reversible electrical breakdown.[1,2] The results of high-frequency noise measurements at electric fields below the breakdown field will be described. The samples consisted of indium-doped germanium with N_A-N_D in the 1 to 5×10^{15}/cc range, and with diffused indium p^+-p contacts. The noise current, $\langle i\rangle^{\frac{1}{2}}$, was found to be "white" over the entire frequency range measured, 0.3 Mc/sec. It was further found that the magnitude of the current noise could be approximated by the shot-noise type relation $\langle i\rangle^2\approx2e(I-I_0)$ where I is the actual sample current and I_0 is the product of the zero-field sample conductivity and the applied emf. These results were found to hold both when the samples were in the cold dark and when they were exposed to room temperature radiation.

[1] N. Sclar and E. Burstein, J. Phys. Chem. Solids 2, 1 (1957).
[2] S. H. Koenig and G. R. Gunther-Mohr, J. Phys. Chem. Solids 2, 268 (1957).

V12. Electrical Transport Effects in Nearly Pure n-Type Silicon. DONALD LONG AND JOHN MYERS, *Honeywell Research Center.*—Careful measurements were made of temperature and magnetic field dependences of the resistivity, Hall effect, and magnetoresistance in samples of nearly pure n-type silicon between 30° and 400°K. The data are compared with a model, which assumes combined intravalley and intervalley lattice scattering plus whatever small amount of impurity scattering is needed. Recent accurate determinations of the conduction band structure and lattice vibrational spectrum indicate that the intervalley phonons occupy two rather narrow energy ranges centered on energies corresponding to about 650° and 200°K. Our model approximates the general situation with single phonons at each of these two energies, and gives a good quantitative description of all the weak magnetic field data when the 650°K phonon scatters roughly as strongly at room temperature at the intravalley acoustic phonons, and the 200°K phonon scatters only weakly. Our data on the field dependence of the longitudinal magnetoresistance and on the complete weak-field magnetoresistance indicate that the intravalley acoustic scattering must be anisotropic; the ratio of relaxation times parallel and perpendicular to an energy-spheroid axis is in the vicinity of $\tau_{\parallel}/\tau_{\perp}=\frac{1}{3}$.

V13. Galvanomagnetic Properties of Medium Angle Grain Boundaries in n-Type Germanium. G. LANDWEHR AND P. HANDLER, *University of Illinois.*—Conductivity, reduced Hall-constant, and magneto-resistance of grain boundaries in n-type Ge were measured as functions of temperature between 240 and 80°K. The samples were cut from a bicrystal with a tilt angle of 20° between two [100] axis. Indium dots were alloyed to the specimens which simultaneously made ohmic contacts to the p-type space charge region of the grain boundary and rectifying contacts to the 2Ω cm n-type bulk. All measured quantities were rather temperature independent indicating degeneracy of the holes in the grain boundary region. The conductivity per square was ~270 μmhos/sq at 240°K, increased about 15% at 150°K and then decreased slowly. The Hall-mobility was about 400 cm²/vsec at 240°K and 550 cm²/vsec at 80°K, going through a flat maximum of 650 cm²/vsec at ~120°K. The transverse magneto-resistance was approximately 3×10^5 cm⁴/v²sec² over the entire temperature range. No longitudinal effect was observed. Reduced Hall-constant and magnetoresistance were found to be independent of the magnetic field up to 0.7 Wb/m², the maximum field used. Within the investigated temperature range magnetoresistance and Hall-mobility in the grain boundary region are similar to these quantities in p-type Ge containing $\sim10^{18}$ acceptors/cm³. Also, the observed mobility is of the same magnitude as is found in clean surfaces.

V14. Field Effect Experiments on Oxidized Germanium. D. R. FRANKL AND A. FEUERSANGER, *Sylvania Research Laboratories.*—Germanium surfaces are prepared by oxidation (several hours at 550°C in wet O_2) following diamond polishing without etching. The surfaces are strongly *n*-type and, on *p*-type and near intrinsic samples, have a high ac field-effect mobility. The conductance changes for large values of induced negative charge are too large to be accountable by completely diffuse surface scattering. Analysis of the data on the assumption of completely specular surface scattering indicates low density of fast surface states over a considerable range about the mid-gap. Heat treatment in argon instead of O_2 leaves a larger density of states. Dc field effect measurements were also made and indicate a highly nonuniform energy distribution of slow surface states over the limited range of surface potentials that could be reached. The relaxation is roughly exponential in the region where the density is small, but strongly nonexponential elsewhere.

WEDNESDAY AFTERNOON AT 2:15

WSU McGregor Memorial

Conference Center Room L

(J. J. LOFERSKI presiding)

Irradiation Effects: Silicon and Germanium

VA1. Mobility of Radiation Induced Defects in Germanium.* P. BARUCH,† *Bell Telephone Laboratories.*—An experiment has been carried out to measure the mobility of radiation induced defects in germanium. Indium alloy diodes have been bombarded at −30°C with 1.0-Mev electrons, the density of fixed charged centers being determined through measurements of the diode capacity. After irradiation, the diodes were annealed from 0° to 70°C, in different steps with and without an electric field obtained by reverse biasing the junction. No effects, caused by the presence of the electric field, could be observed below 55°C in times of the order of a day. Above this temperature, an effect was observed which could be ascribed to the migration of a negatively charged defect with a mobility of the order 10^{-14} v/cm² sec at 70°C. The identification of this defect with those observed in conductivity and Hall coefficient experiments is dubious, because of the different state of charge of the defect centers in a space charge region.

* This work was supported by the Wright Air Development Division of ARDC of the U. S. Air Force.
† Permanent address: Ecole Normale Superieure, Laboratoire de Physique, Paris V, France.

VA2. High-Energy Electron Irradiation of Germanium at 78°K. V. A. J. VAN LINT, E. G. WIKNER, J. W. HARRITY, AND H. HORIYE, *General Atomic.**—Samples of *n*-type germanium were irradiated by 25 Mev electrons at 78°K until they were converted to *p* type. Measurements performed during irradiation included conductivity, Hall coefficient, and excess-carrier lifetimes. The following conclusions have been made from these data. 1. Appreciable annealing of the radiation-induced changes occurred during a few minute warming to 275°K. 2. The initial change of Hall coefficient implied a carrier removal rate of 4.0 electron/cm of 25-Mev electron path. 3. When the Fermi level crosses a point 0.10 ev below the conduction band, the carrier removal rate falls to 0.019 electron/cm of path. 4. The electron mobility is decreased markedly during irradiation by impurity scattering but the hole mobility remains at the value determined by lattice scattering. 5. Two-hole trapping levels were observed at 78°K having activation energies of 0.27 ev and 0.15 ev.

* John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.

VA3. Thermal Neutron Radiation Effects in Semiconductors. J. W. CLELAND AND J. H. CRAWFORD, JR., *Oak Ridge National Laboratory.**—Monoenergetic electron irradiation experiments on Ge and Si have indicated a threshold energy for the formation of stable acceptor centers of ~15 ev. The average value of the kinetic energy of recoil following thermal neutron absorption and capture gamma ray emission is 180 ev in Ge and 780 ev in Si; hence, multiple defect production might be expected to result from the energetic recoil. The additional recoil energy upon later transmutation of certain isotopes is negligible; hence, interstitial donor and acceptor type impurities might be expected from radioactive decay. Analysis of different experiments on Ge and Si indicates almost identically one electron removed from conduction for each thermal neutron absorption and recoil; thus, multiple defect production is not observed. Subsequent conductivity measurements during radioactive decay indicate apparently identical behavior for transmutation produced chemical impurity donors and acceptors that are presumably interstitial from recoil, or those that are presumably substitutional from thermal annealing experiments.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

VA4. Annealing of Radiation-Induced Recombination Centers in Germanium. O. L. CURTIS, JR. AND J. H. CRAWFORD, JR., *Oak Ridge National Laboratory.**—An experimental survey employing minority carrier lifetime has been made of the annealing above room temperature of recombination centers induced by 14-Mev monoenergetic neutrons, fission neutrons, and Co^{60} gamma rays. In each case, three specimens were used of the following type and resistivity: 2 ohm-cm *p* type, 2 ohm-cm *n* type, and 15 ohm-cm *n* type. A large difference in the annealing behavior was observed among the three types of radiation damage as well as the three types of specimens. To cite two examples: All the 2 ohm-cm *n*-type specimens showed strong annealing at 104°C, while the 15 ohm-cm *n*-type specimens displayed almost no annealing at 104°C. The 2 ohm-cm *p*-type specimen irradiated with Co^{60} gamma rays showed complete recovery at 200°C, while the neutron-irradiated specimens both showed only about one-half recovery. More detailed studies are now in progress, including the effect of different impurities.

* Oak Ridge National Laboratory is operated by the Union Carbide Corporation for the U. S. Atomic Energy Commission.

VA5. Effect of Dissolved Oxygen on Radiation Damage in *n*-Type Silicon. E. SONDER AND L. C. TEMPLETON, *Oak Ridge National Laboratory.**—By using Hall-effect measurements, the effects of Co^{60} gamma-ray damage has been studied in

n-type silicon grown from quartz crucibles (therefore containing dissolved oxygen) and in low-oxygen-content silicon grown by the floating zone technique. In the case of 2 ohm-cm oxygen-containing material, one discrete net acceptor level located 0.17 ev below the conduction band is introduced by the irradiation at the rate of approximately 1.3×10^{-2} trap/incident photon. However, in silicon of similar resistivity, containing less than 10^{16} oxygen atoms per cm^3, there is clear evidence of the introduction of two net acceptor levels, one at 0.17 ev and another at 0.47 ev below the conduction band. The introduction rate of these is 0.8×10^{-2} and 1.0×10^{-2} trap/incident photon, respectively.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

VA6. Infrared Absorption in Irradiated Silicon, Oxygen-Dependent.* A. K. RAMDAS AND H. Y. FAN, *Purdue University.*—Several additional lattice absorption bands have been observed in electron or neutron bombarded silicon between 9–14 μ. Wavelengths of the peaks in microns are: 9.79, 9.97, 10.35, 10.42, 11.42, 11.56, 11.98,[1] 12.33; strong peaks are underlined. These bands are not observed in bombarded, floating zone samples. Two of the bands, 9.97 and 12.33, were not found in all samples; they decreased considerably after ½-hr annealing at 100°C. Annealing at 200°C was made for different time intervals. The 9.79 band annealed the fastest, the 10.35 and 10.42 bands annealed slower, and the 11.42, 11.56 and 11.98 bands decreased only slightly after 5½ hr of annealing. With annealing at 200°C, new bands appeared at 10.28, 10.5, 10.95, 11.29, and 11.68 μ, respectively. The 10.95 band grew steadily with annealing whereas the other three increased little after the first ½ hr. Two observations are noteworthy: (a) the bands appear to saturate with bombardment with little decrease of the normal 9 μ oxygen band, (b) the bands are very weak if the sample was preheated at 1000°C and the 9-μ band was suppressed.

* Work supported by a Signal Corps Contract.
[1] This band has been reported by Corbett, Watkins, and Chrenko, Bull. Am. Phys. Soc. Ser. II, **5**, 25 (1960).

VA7. Infrared Absorption in Irradiated Silicon, Oxygen Independent.* H. Y. FAN AND A. K. RAMDAS, *Purdue University.*—By studying crucible grown and floating zone samples bombarded together, irradiation introduced absorption bands at 1.8, 3.3, 3.9, 18.2, and 20.5 μ[1] were found to be independent of the oxygen content in the samples. The oxygen content was checked by the strength of the 9-μ absorption band. The 20.5 and the newly found 18.2 lattice bands and the 3.9 electron excitation band were observed in neutron bombarded[2] samples. The 20.5 band was found to be also independent of other doping impurities. The 3.3 band was observed in n-type samples with electron as well as neutron irradiations. Its production is independent of the oxygen content and the donor impurity. The 1.8 band is also independent of the doping impurity. However, with neutron irradiation it is produced with equal intensity in both floating zone and crucible grown samples, but appears only in the crucible grown samples with electron irradiation. The absence of 1.8 band in floating zone samples cannot be attributed to high density of dislocation that is common to such samples.

* Work supported by a Signal Corps Contract.
[1] H. Y. Fan and A. K. Ramdas, J. Appl. Phys. **30**, 1127 (1959).
[2] We are indebted to Dr. J. H. Crawford and Dr. J. W. Cleland of Oak Ridge National Laboratory for the irradiations.

VA8. Identification of the A Center in Irradiated Silicon I: Spin Resonance. G. D. WATKINS AND J. W. CORBETT, *General Electric Research Laboratory.*—The previously proposed[1] model of the A center, which is the dominant defect in irradiated pulled silicon crystals, is that of a lattice vacancy with an oxygen atom bridging two of the four broken bonds. In this model, the spin resonance arises from an electron trapped in the other two broken bonds. We have studied the effect of uniaxial stress on the spin resonance of the A center. Under stress, the amplitudes of the individual resonance components (which correspond to different orientations of the defect in the crystal) are observed to change. Two mechanisms are found for this change. First, the energy of the electron trapped at the A center is raised or lowered depending upon the orientation of the defect with respect to the stress. The amplitudes in the spectrum therefore change as a result of electronic redistribution between the defects. Second, the defects themselves can reorient under the applied stress. These two effects are separable and a quantitative study of their magnitudes and signs, as well as their rates, will be presented. The results confirm many of the important features of the model described above.

[1] G. D. Watkins, J. W. Corbett, and R. M. Walker, J. Appl. Phys. **30**, 1198 (1959); G. Bemski, J. Appl. Phys. **30**, 1195 (1959).

VA9. Identification of the A Center in Irradiated Silicon II: Infrared. J. W. CORBETT, G. D. WATKINS, AND R. S. MCDONALD, *General Electric Research Laboratory.*—The infrared oxygen vibration band at 12 μ observed in irradiated silicon[1] has been studied while applying a uniaxial stress to the specimen. A preferential alignment of the defect giving rise to this band has been detected by a change in the relative absorption of light polarized parallel and perpendicular to the stress direction. By applying the stress *in situ* and varying the temperature, it was possible to demonstrate that the rate at which the defect reorients is identical to that found by spin resonance for the A center in the previous abstract. This shows that the 12-μ band arises from the A center, and gives conclusive proof that the A center involves an oxygen atom. Moreover, the quantitative comparison of the magnitude and sign of the observed effects with the known behavior of the A center under stress (see previous abstract) shows that the configuration of the oxygen is as in the proposed model.

[1] J. W. Corbett, G. D. Watkins, and R. M. Chrenko, Bull. Am. Phys. Soc. II, **5**, 25 (1960).

VA10. Solid-State Detector for Penetrating and Minimum Ionizing Particles. J. D. VAN PUTTEN, JR. AND J. C. VANDER VELDE, *The University of Michigan.*—By extending the technique of Davis,[1] who used 5.3-Mev α particles to measure electron lifetimes and mobilities in gold-doped silicon, we have detected individual minimum ionizing particles (electrons) which penetrate the full depth (5 mm) of the crystal. Since the electrons produced by ionization of a fast particle can be collected from throughout the whole crystal, this type of counter can be used to detect high-energy particles with a pulse height that should give a direct measure of dE/dx; the only limitation being the statistical fluctuation in the energy loss. Preliminary measurements with 5.3-Mev α particles (range 23 μ) and 7.8-Mev deuterons (range 0.28 mm) indicate that essentially all of the liberated charge is being collected, with an energy resolution of $\pm2\%$. Results on the pulse height distribution from 10-Mev protons (range 0.72 mm) and a description of the counter will be presented.

[1] W. D. Davis, Phys. Rev. **114**, 1006 (1959).

VA11. Evidence For Fast Damage Annealing Processes in Semiconductor Devices.* JEROME ROTHSTEIN, *Edgerton, Germeshausen and Grier, Inc.*—Germanium transistors were exposed to Godiva II and Triga pulses. I_{co} and H_{fe} were monitored. I_{co} response was separated into sum of (a) current pulse of same shape as radiation pulse, (b) permanent change proportional to integrated radiation pulse, (c) transient decay. Superpositions of (a) and (b) alone gave excellent agreement with rising edge of pulse and beginning of decay, or with rising edge of pulse and final level, with different (b) amounts

in the two cases. Decay times of approximately 0.1(10) msec were found for (c) with Godiva (Triga), calculated as decay between the two cases of superposed (a) and (b). We ascribe (a) to gamma induced hole-electron pairs, (b) to integrated neutron damage, (c) to rapidly annealing neutron damage, electronic, surface, or isotope decay effects. Radiation pulse time constants were 0.04(5) msec for Godiva (Triga) and so separable from device relaxation. Fast decay may be recombination of electrons and holes or of close vacancies and interstitials, slow decay vacancy-interstitial or surface relaxation, with isotope decay unlikely.

* Sponsored by U. S. Army Signal Engineering Laboratories.

WEDNESDAY AFTERNOON AT 2:15

Auditorium, Rackham Memorial

(P. M. MARCUS presiding)

Invited Paper

W1. Temperature Dependence of Infrared Lattice Vibration Spectra of Alkali Halides. MARVIN HASS, *U. S. Naval Research Laboratory.* (30 min.)

Lattice Vibrations

W2. Infrared Lattice Vibration Spectrum of LiH.* A. S. FILLER AND E. BURSTEIN, *University of Pennsylvania.*—Reflection measurements were made from 2 to 50 μ on crystals supplied by Foote Mineral Co. LiH exhibits a strong reflection peak in the region from 550 to 1100 cm^{-1}, and a minimum at $\nu_m = 1260$ cm^{-1}. The general features of the reflection curve can be fitted reasonably well by a single oscillator dispersion relation whose parameters are determined from ν_m, ϵ_∞(high frequency dielectric const) $= 3.61$,[1] and the choice of ν_l(transverse optical frequency) $= 600$ cm^{-1}. From these values, one obtains the following parameters: ϵ_0(static dielectric constant) $= 12.5$, ν_l(longitudinal optical frequency) $= 1120$ cm^{-1} and e_s*(the Szigetti dynamic effective ionic charge) $= 0.52e$, which is considerably smaller than the values reported for the other alkali halides. The small effective charge is attributed to the large overlap between the H^- and Li^+ ions indicated by theoretical calculations and to a relatively large distortion of the H^- ion (ionic polarizability $\alpha_{H^-} = 2.4$ A^3) compared to that of the Li^+ (ionic polarizability $\alpha_{Li^+} = 0.03$ A^3) The ratio of the negative ion to positive ion polarizabilities for LiH($\alpha_{H^-}/\alpha_{Li^+} = 80$) is greater than the corresponding values for those alkali halides for which e_s* have been determined.

* Research supported by the U. S. Atomic Energy Commission.
[1] E. Staritzky and D. I. Walker, J. Anal. Chem. **28**, 1055 (1956).

W3. Impurity Induced Infrared Lattice Vibration Absorption. R. F. WALLIS AND A. A. MARADUDIN,* *U. S. Naval Research Laboratory.*—Impurities are known to affect vibrational properties of crystals by modifying the distribution of normal mode frequencies and altering the nature of the atomic displacements in the neighborhood of the impurities. We have calculated the effects of isotopic impurities on the lattice vibrational optical absorption of both monatomic and diatomic linear chains of alternately charged particles. It is found that even with the harmonic approximation and the use of the cyclic boundary condition, the presence of impurities leads to a broad absorption of the low frequency side of the main maximum. This is in contrast with the delta-function type of absorption at the optical frequency predicted by these models in the absence of impurities. For those cases in which discrete frequencies associated with localized vibrational modes occur, absorption at these isolated frequencies also occur. This latter absorption can take place at frequencies higher that of the main maximum. A discussion will be given of the relation between the results of our calculations and available experimental data.

* Permanent address: University of Maryland.

W4. Lattice Vibrational Spectra of Germanium-Silicon Alloys. R. BRAUNSTEIN, *RCA Laboratories.*—The vibrational spectra of Ge-Si alloys were observed in the spectral range from 8–48 μ. It was possible to follow the evolution of the spectra from pure Ge through the alloys to pure Si and to identify some of the two phonon summation bands. The gross features of the spectra reveal a continuous variation of the positions and the intensities of the absorption bands as a function of composition; however, the strongest Ge-like band sum (*TA,TO*) approaches but does not merge with the equivalent Si-like band. It is possible to observe both of these bands in a sample of 81 mol % Si in Ge. Some of the features of the spectra can be explained by the existence of short range order in the alloys. By identifying equivalent bands in the alloys as compared to the assignments of the bands in pure Ge and Si, the optical and acoustical vibration frequencies near the edge of the reduced zone were determined throughout the alloy system. The appearance of new bands, not present in either pure Ge or pure Si, due to the addition of small amounts of Si to Ge or vice versa, which occur near the fundamental optical vibration frequency of the dominant constituent, are identified as single phonon "vibrational impurity bands."

W5. Lattice Vibration Spectrum of Bismuth.* S. H. KOENIG, *IBM, Watson Laboratory,* AND J. YARNELL, *Los Alamos Scientific Laboratory.*—The acoustic branches of the lattice vibration spectra of bismuth have been measured along the trigonal and binary crystallographic axes. Measurements were made by studying the inelastic scattering of a monochromatic beam of neutrons incident on a single bismuth crystal. The bismuth lattice may either be regarded as face-centered cubic slightly elongated along a trigonal direction with two atoms per unit cell, or as a slightly distorted *simple* cubic lattice. There should be both acoustic and optical modes in the spectrum, with, however, near degeneracy of the transverse acoustic (TA) and optical branches (TO) and of the longitudinal acoustic (LA) and optical branches (LO) at the intersection of the trigonal axis with the zone boundary. In addition, the TA and TO modes at the center of the zone, which in the diamond lattice are degenerate, are expected to

differ by something like a factor of two in energy. Though the optical modes have not as yet been observed, the data for the TA mode in the trigonal direction show almost no dispersion over the entire zone, tending in part to justify the basis of the previous statements. The influence of the details of the vibration spectrum on electrical transport will also be discussed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

W6. Lattice Vibrations in Lead. III. B. N. BROCKHOUSE, G. CAGLIOTI, M. SAKAMOTO, R. N. SINCLAIR, AND A. D. B. WOODS, *Chalk River Laboratories.*—Previously reported measurements[1] of the dispersion ($\nu(\mathbf{q})$) relations of the lattice vibrations of lead have been continued, using, for the first time, a new control unit which enables energy distributions to be obtained at a constant wave vector $\mathbf{q}$. The (100) plane of the crystal was horizontal (in previous measurements the (110) plane was horizontal), enabling measurements of the second $[\zeta,\zeta,0]T$ branch and two $[\zeta,1,0]$ branches to be obtained at 100°K, as well as further measurements in both $[\zeta,0,0]$ branches and the $[\zeta,\zeta,0]L$ branch. The temperature dependence of both longitudinal and transverse branches in the $[\zeta,0,0]$ direction has been measured between 100° and 425°K. The behavior of these branches is being studied at 570°K. The frequencies of zone boundary positions are (in units of 10^{12} c/s), for $[\zeta,0,0]L$: $T=100$°K, $\nu=1.89\pm0.03$; $T=295$°K, $\nu=1.92\pm0.03$; $T=425$°K, $\nu=1.86\pm0.04$, and for $[\zeta,0,0]T$: $T=100$°K, $\nu=0.91\pm0.01$; $T=213$°K, $\nu=0.93\pm0.01$; $T=295$°K, $\nu=0.97\pm0.01$; $T=425$°K, $\nu=0.96\pm0.02$. Fourier analysis of these curves indicate that long range forces are prominent especially at the lowest temperatures. The widths of the phonons increase with increasing temperature, but this effect is greater for values of $\mathbf{q}$ near the zone boundary than for small $\mathbf{q}$.

[1] Bull. Am. Phys. Soc. Ser. II, 5, 39 (1960).

W7. Effect of Free Electrons on Lattice Vibrations. W. C. OVERTON, JR., *U. S. Naval Research Laboratory.*—The effect of free electrons on the vibration spectra of face-centered cubic lattices is determined from the comparison of the properties of the surfaces of constant frequency in the Brillouin zone of lattices represented by two models for the interatomic force constants, namely, the two-force-constant central-force model and this same lattice immersed in the free electron gas (de Launay's model).[1] The properties are examined for the representative case of copper, in which experimental elastic constants are used to give α and γ for the two-force model and the same α and γ and also ξ, the third constant of de Launay's model. The cubic secular determinant of this latter model has been found to be factorable in both the (100) and (110) planes, thus allowing simplification of the numerical problem of locating the critical points in these planes. Compared are the locations of the critical points, the geometry of the critical point surfaces, their frequencies, and their contributions to the frequency distributions. The effect on the specific heat due to immersing the two-force model lattice in the electron gas will be discussed.

[1] J. de Launay, *Solid State Physics*, edited by Seitz and Turnbull (Academic Press, Inc., New York), Vol. 2.

W8. Application of Summability Methods to Specific Heat Calculations. A. A. MARADUDIN AND G. H. WEISS, *University of Maryland,* AND R. SACK, *British Rayon Research Association.*—In 1914, Thirring[1] obtained an expansion for the vibrational contribution to the specific heat of a crystalline solid in powers of $1/T$. The coefficients of this series are proportional to successive moments of the frequency spectrum. Thirring's expansion converges only for $T>\Theta/2\pi$, where $\Theta=\hbar\omega_L/k$ and ω_L is the maximum normal mode frequency. The series, in addition, converges very poorly near its radius of convergence and is completely useless there. It can, however, be analytically continued beyond its radius of convergence by means of the Euler transformation,[2] which, in addition, greatly increases the rate of convergence of the series near the radius, so that only about seven moments are required for better than three figure accuracy for the specific heat of a face-centered cubic lattice at this point. Other methods for summing divergent series can also be used effectively. Some examples of the use of these methods will be presented.

[1] H. Thirring, Phys. Z. 14, 867 (1913); ibid, 15, 127, 180 (1914).
[2] K. Knopp, *Theory and Application of Infinite Series* (Blackie and Son Limited, London, England).

W9. Phonon Enhancement of the Electron Specific Heat of the Alkali Metals. JOHN J. QUINN, *RCA Laboratories.*—The contribution of the electron-phonon interaction to the energy of a single electron is studied as a function of the electron momentum by means of the self-energy approach.[1] In the present problem, the electron self-energy arises from the virtual emission and reabsorption of phonons. Feynman propagator techniques are used to evaluate the first-order contribution to the self-energy; it is found that normal and umklapp processes contribute about equally to this order. The electron-phonon interaction gives rise to an enhancement of the Sommerfeld electronic specific heat. The enhancement factor determined from the first-order calculation decreases with increasing electron density going from 1.44 for cesium ($9.35\cdot10^{21}$ electrons/cm^3) to 1.26 for lithium ($4.85\cdot10^{22}$ electrons/cm^3).

[1] J. J. Quinn and R. A. Ferrell, Phys. Rev. 112, 812 (1958).

W10. Optical Activity of the Lattice Vibrations in Solid Hydrogen. J. D. POLL AND J. VAN KRANENDONK, *University of Toronto.*—The vibrational, rotational, and translational motions of the molecules in solid hydrogen are infrared active in virtue of the electric dipole moments induced in the molecules by the intermolecular forces. These induced dipole moments depend strongly on the intermolecular separations. The most prominent parts of the infrared spectrum of solid hydrogen therefore consist of the phonon branches arising from transitions, in which one or more phonons are created in the absorption process. In contradistinction to the single transitions in which one molecule makes a rotational or vibrational transition and no phonons are involved, the phonon branches are not appreciably affected by the cancellation effect. The intensity of the single transitions is reduced by one to two orders of magnitude, since the dipole moments induced in a central molecule and the surrounding molecules tend to cancel one another as a result of the symmetry of the crystal lattice. The calculation of the intensity of the phonon branches and the comparison with the experimental data will be discussed.

W11. Fine Structure of the Rotational Infrared and Raman Spectra of Solid Hydrogen. J. VAN KRANENDONK, *University of Toronto.*—In solid parahydrogen, the excited rotational states are broadened by the anisotropic intermolecular forces into rotational energy bands. The resulting fine structure of the induced infrared and Raman spectra has been calculated for arbitrary anisotropic intermolecular forces. A comparison with the experimental data yields detailed information about the nature of the anisotropic forces in solid hydrogen. In the presence of a vibrating molecule in the crystal, a number of bound states split off from the bottom of the rotational energy bands as a result of the negative rotation-vibrational interaction in a molecule. The frequencies and splittings of the corresponding rotation-vibrational infrared absorption and Raman lines have been calculated with the help of the im-

purity state theory developed by Koster and Slater.[1] In the presence of ortho molecules in the parahydrogen crystal, evidence is obtained for the preferred occurrence of the ortho molecules in the form of nearest neighboring pairs. The importance of this clustering tendency for the theory of the specific heat anomaly in solid ortho-para mixtures will also be discussed.

[1] G. F. Koster and J. C. Slater, Phys. Rev. 95, 1167 (1954).

WEDNESDAY AFTERNOON AT 2:15

WSU Community Arts Auditorium

(R. HERMAN presiding)

Insulators

X1. Self Diffusion of Chlorine in Sodium Chloride. NEAL LAURANCE, *University of Illinois.*—The diffusion coefficient of Cl^{36} in NaCl has been measured in the temperature range from 520° to 740°C. Diffusion was measured in pure Harshaw crystals and in crystals containing from 0.01 to 0.1 mole percent Ca. The diffusion coefficient in pure crystals could be represented by the equation $D=56\exp(-2.12\text{ ev}/kT)$ cm²/sec. The diffusion coefficient in crystals containing calcium was smaller than that measured in pure crystals by a factor of from 5 to 10. Over the range of impurity concentration employed the diffusion coefficient was insensitive to differences in calcium concentration. The activation energy for diffusion in crystals containing calcium was about 2.5 ev. These results are in disagreement with the predictions of the mass action law if motion of negative ion vacancies is assumed as the mechanism of transport. The dependence of the diffusion coefficient on calcium concentration is in qualitative agreement with the expected behavior of vacancy pairs. The observed activation energy, however, is 1 ev greater than that estimated theoretically for diffusion via vacancy pairs.

X2. Pressure Dependence of Ionic Conductivity in Some Alkali Halides.* C. B. PIERCE AND DAVID LAZARUS, *University of Illinois.*—The ionic conductivities of NaCl, KCl, and RbCl, all with suitable added divalent impurities, have been measured at elevated temperatures and under hydrostatic pressures of up to 9000 kg/cm². The variation with pressure is found to be quite large. For example, at a given temperature in the extrinsic region the conductivity of NaCl decreases by an order of magnitude in going from 1 to 9000 kg/cm². The activation volume for motion of a mole of vacancies in NaCl is found to be of the same order as the molecular volume and to decrease with increasing temperature. Also, the activation energy for NaCl is found to decrease measurably with increasing pressure.

* Supported in part by the U. S. Atomic Energy Commission.

X3. A Quenching Effect in the Ionic Conductivity of NaCl Crystals Doped with Divalent Impurities. A. S. NOWICK AND R. W. DREYFUS, *IBM Yorktown Research Center.*—An increase in the electrical conductivity, σ, up to ten times was observed at temperatures below 0°C when NaCl crystals doped with Mg^{++}, Mn^{++}, Ca^{++}, and Cd^{++} were cooled from 150°C to −50°C in about 10 min. This effect is attributed to the freezing-in of a nonequilibrium state of dissociation of complexes consisting of the divalent ion associated with a cation vacancy. On this basis, it is predicted that the variation of the conductivity in the nonequilibrium range with temperature should give an activation energy equal simply to the migration energy of a cation vacancy, $\epsilon_m{}^+$. The value obtained from the curve of $\log\sigma T$ vs T^{-1} during warmup from −50°C to 0°C is $\epsilon_m{}^+=0.75\pm0.05$ ev. This value is lower than that suggested from earlier work,[1] but is consistent with the slope of the conductivity curve just below the intrinsic range. The isothermal recovery of the conductivity has also been studied and found to obey first-order kinetics. This fact eliminates the possibility that the process involves the migration of free cation vacancies to dissociated impurity atoms.

[1] H. W. Etzel and R. J. Maurer, J. Chem. Phys. 18, 1003 (1950).

X4. Dielectric Relaxation in Sodium Chloride Crystals Containing Divalent Impurities. R. W. DREYFUS, *IBM Yorktown Research Center.*—Dielectric relaxation in sodium chloride crystals is used to observe the motion of cation vacancies associated with such added impurities as Mn^{++}, Mg^{++}, and Cd^{++}. The present measurements are of the decaying current following the application of a dc electric field. The current is observed to decay as $\exp(-t/\tau)$ over one and one-half orders of magnitude with values of τ in the range 0.1 to 100 sec for temperatures of +30° to −80°C. High temperature measurements of the same effect have been made earlier using ac bridge methods.[1] In both types of observations, the predominant relaxation is attributed to the motion of cation vacancies between two lattice sites located at a distance $\sqrt{2}a$ from an impurity atom, where a is ½ the edge of the unit cell. The present results, combined with the previous work,[1] gives: $\tau^{-1}=2\nu_1=1.1\times10^{14}\exp[-0.69(\text{ev})/kT]\,\text{sec}^{-1}$ for NaCl:Mn (where ν_1 is the vacancy jump frequency in a given direction). A much slower additional relaxation is also observed which is attributed predominantly to cation vacancies occupying sites $2a$ away from the impurity atom. The relative increase of this second relaxation with decreasing impurity radius supports this hypothesis.

[1] G. D. Watkins, Phys. Rev. 113, 91 (1959).

X5. Anomalous Microwave Dielectric Constant of Silver Bromide. GLEN E. EVERETT,* A. W. LAWSON, AND G. E. SMITH,† *University of Chicago.*—The previously reported maximum in the 23-kMc dielectric constant of silver bromide near 350°C is explained as arising from a phase shift between the applied field and the response of the ionic defects. Because associated Frenkel pairs and recombination-dissociation effects contribute to the loss mechanism as well as isolated defects, the behavior of the dielectric constant is more complicated than for a simple relaxation mechanism. Analysis of this quantity in conjunction with low frequency conductivity data permits an estimate of the number, Na, of associated pairs in terms of the number, N_f, of dissociated pairs. The ratio is $Na/N_f=5\pm1$ at 410°C. The presence of a high density of associated pairs does not affect transport properties materially, but would explain the anomalously high enthalpy and volume expansions observed near the melting point.

* National Science Foundation Predoctoral Fellow.
† Now at Bell Telephone Research Laboratories.

X6. Exciton Series Structure in the Photoelectric Emission from the Alkali Iodides. E. A. TAFT AND H. R. PHILIPP, *General Electric Research Laboratory.*—Structure appears in the photoelectric yield of the alkali iodides when *F* centers are are present. At the position of the first fundamental absorption peak, the yield rises to a sharp maximum. Here, excitons are formed which ionize *F*-centers in a secondary process. At 80°K, an additional peak may be clearly resolved. It occurs at an energy which is near the threshold for band-to-band optical transitions. Fischer and Hilsch[1] have recently completed a new and detailed study of the optical absorption of the alkali iodides. At 14°K, a small peak is resolved in the absorption spectrum, which they have associated with the second and higher members of the first exciton series. The previously unexplained photoelectric emission peak is substantially coincident with the new peak which Fischer and Hilsch have discovered. Their work provides an attractive explanation for the photoelectric result, namely that the second exciton peak stimulates emission from *F* centers just as the first one does. Photoelectric detection appears to be very sensitive for this purpose since band-to-band absorption does not contribute to photocurrent. Thus, the structure may be resolved even at room temperature.

[1] F. Fischer and R. Hilsch, Nachr. Akad. Wiss. Gottingen, Math.-physik, Kl. **8** (1959).

X7. Low-Temperature Luminescence of "Pure" Alkali Halides. H. V. WATTS, L. REIFFEL AND M. D. JONES, *Armour Research Foundation.*—The scintillation properties of "pure" (unactivated) CsI, CsBr, and KI have been studied for α-particle and gamma-ray excitation over the temperature range 4° to 300°K. The pulse heights and decay constants increase as the temperature decreases. CsBr and KI exhibit a saturation value in pulse height and decay constant at temperatures below 80°K. CsI exhibits a definite maximum in pulse height at a temperature of about 40°K, while its decay constant appears to remain constant below 40°K. This behavior is similar to that observed by Van Sciver[1] for NaI. The pulse heights are comparable to those observed from impurity-activated alkali halides such as NaI(Tl) and the observed decay constants are in the 0.1- to 2.0-μsec range. A tentative explanation for the shapes of the pulse height vs temperature and decay time vs temperature curves is given. Data regarding the spectral character of the luminescence and results for other alkali halides will also be presented.

[1] W. J. Van Sciver and L. Bogart, Inst. Radio Engrs. Trans. on Nuclear Science, **NS-5**, 3, 90 (1958).

X8. Absorption Spectra of KCl:Tl at High Temperatures. DAVID A. PATTERSON, *U. S. Naval Research Laboratory.*—The absorption spectra of several single crystals of KCl containing different amounts of Tl have been measured from room temperature to 560°C. As the temperature is increased, the "*C*" band at 196 mμ decreases and the "*B*" band at 209 mμ apparently increases. The large increase in the "*B*" band reported by Forro is not observed. A further difference is found in the position of the absorption edge at high temperatures which, in the present work, is approximately 8 mμ to longer wavelengths than that reported by Forro. Both the shape and the area of the complex "*A*" band at 247 mμ are found to depend on Tl content and on temperature. The area decreases with increasing temperature at a rate which is inversely dependent on the Tl content. This is correlated with the concentration-dependent growth with temperature of the long wavelength tail of the complex band. It is concluded that the complex "*A*" band consists of three components at approximately 247, 254, and 262 mμ with each due to a different center.

X9. Pressure Effects in the Luminescence of Activated Alkali Halides.* R. M. NORTON AND L. REIFFEL, *Armour Research Foundation.*—Investigation of the effects of pressure on the phosphorescent decay of activated alkali halides is continuing. The response of NaI(Tl), excited by Ir^{192} gamma radiation, for pressures up to 50 000 psi has already been reported.[1] Observations on single crystal CsBr(Tl), KI(Tl), KCl(Tl), and NaCl(Ag) will be presented over a comparable range of pressures. As expected, the thallium-activated materials are qualitatively similar while the phosphorescence of NaCl(Ag) exhibits appreciable pressure sensitivity only after about 20 min of decay at 18°C.

* Supported in part by the Air Force Office of Scientific Research.
[1] L. Reiffel, Phys. Rev. **114**, 1493 (1959).

X10. Oscillator Strengths of Three Optical Absorption Bands in Quartz and Fused Silica. R. A. WEEKS AND C. M. NELSON, *Oak Ridge National Laboratory.**—Three absorption bands observed in γ-ray and neutron irradiated quartz and silica have a correlation factor of one with three paramagnetic defects observed by the electron spin resonance (ESR) technique.[1] It is assumed that the defects producing the optical bands are the same as those giving rise to the ESR spectra. The three optical bands have maxima at 5.4 ev, 5.9 ev, and 7.65 ev. The shape of the 5.4-ev and 5.9-ev bands were in reasonable agreement with a Gaussian function, and it was assumed that the 7.65-ev band could also be described by a Gaussian function. The width at half maximum amplitude of the three bands was 0.8 ev, 0.8 ev, and 0.4 ev, respectively. The concentration of centers was determined by comparing the ESR line intensities with a known amount of diphenyl-picryl-hydrazyl (DPPH). An attempt was made at evaluating the inaccuracies inherent in the use of DPPH as a standard. By using the form of Smakula's equation appropriate for a Gaussian absorption band, the oscillator strengths of the three bands were calculated and are 0.2 ± 0.1, 0.08 ± 0.04, and 0.6 ± 0.3, respectively.

* Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
[1] R. A. Weeks and C. M. Nelson, J. Am. Ceram. Soc. (to be published); C. M. Nelson and R. A. Weeks, Bull. Am. Phys. Soc. Ser. II, **4**, 158 (1959).

X11. Optical Absorption in Iron-Doped Rutile.* R. F. BLUNT, J. H. BECKER, AND H. P. R. FREDERIKSE, *National Bureau of Standards.*—The energy levels in iron-doped rutile are of particular interest since this impurity can lead to extrinsic p-type conduction.[1] Absorption measurements at 300 and 4°K have been made on oriented crystals of TiO_2[2] containing iron (by diffusion from Fe_2O_3). Polarized radiation from ~0.2 to 3 ev was used with $E\perp$ and $E\parallel$ c axis. The samples were subjected to various oxidation and reduction treatments, ranging from 1 atmos of O_2 at 500°C to vacuum reduction at 880°C. The absorption is most pronounced in the visible range, but extends throughout the entire wavelength region with several overlapping bands. The heavily doped crystals are red, while the more lightly doped crystals are yellow. In all cases, the absorption coefficients increase upon passing from the more oxidized to the more reduced state; however, little of the increased absorption can be attributed to the bands which are observed near 1 ev in reduced undoped crystals.[3] A model including Fe^{2+}, Fe^{3+}, and oxygen vacancy levels will be discussed.

* Work supported in part by the Office of Naval Research.
[1] J. Rudolph, Z. Naturforsch. **14a**, 727 (1959).
[2] The undoped crystals were kindly supplied by the Linde Company.
[3] D. C. Cronemeyer, Phys. Rev. **113**, 1222 (1959).

X12. Shock-Induced Luminescence. N. L. COLEBURN, M. SOLOW, AND R. C. WILEY, *U. S. Naval Ordnance Laboratory.*—When a shock wave emerges from the free surface of an illuminated aluminum plate, blue light is emitted from the surface. This is determined in the following experiment: An aluminum plate is treated to give a porous, thick Al_2O_3 surface layer. It is placed under a vacuum and subjected to a plane shock wave

of 270 kb. The surface of the aluminum is illuminated normally with blue light from an argon-flash bomb. The reflected and emitted light normal to the surface is recorded with a smear camera. The mechanism for the generation of the light is postulated as emission from F' centers in the oxide coating. When light ionizes the chemisorbed oxygen on the surface, the oxygen leaves as a gas and exposes the surface F' centers. The light ionizes the centers, causing electron emission and the generation of a surface charge. Since the shock in the aluminum represents a power surge of approximately 10^9 w/cm², it drags with it a sheet of electrons by the electroacoustic effect. When these electrons reach the oxide layer they are accelerated, excite the bulk F' centers, and cause blue light emission.

X13. Capacitance Measurements in Single Crystal TiO_2. R. A. PARKER AND J. H. WASILIK, *National Bureau of Standards* (introduced by H. P. R. Frederikse).—Measurements have been made of the complex capacitance ($C^* = C' - jC''$) of undoped single crystal TiO_2 (rutile) in the c direction in vacuum at 78°, 195°, 273°, and 298°K as a function of frequency between 2×10^1 and 7×10^7 cps with a 0.1-v ac signal. One low frequency loss peak is found at 200 cps. The capacitance and loss of a 2-mm cube are characterized by $2\pi\tau = 1/200$ sec, $\tan\delta_{200\text{Cps}} = 0.8$, and a dielectric constant ϵ' of 170 at 1 Mc, while $\epsilon'_{20\text{Cps}}/\epsilon'_{1\text{ Mc}} = 100$. The loss is directly proportional to the area of the electrodes and depends, but slightly, on the sample thickness, electrode materials, and surface treatment. C_{max}'', $C_{20\text{Cps}}' - C_{1\text{ Mc}}'$, and $1/\tau$ all decrease with decreasing temperature. C' and C'' have been measured as a function of dc bias from 0 to 400 v at 78° and 195°K. C_{max}'' and τ are proportional to V^{-n}, where n is between $\frac{1}{2}$ and 1. This behavior can be explained qualitatively by an electron-deficient barrier layer whose thickness increases with increasing applied voltage. When the dc voltage is changed, effects are observed whose time constants are of the order of hours or even days.

X14. Sidewise Motion of c Domain Nucleation Centers in $BaTiO_3$ (with movies). GORDON L. LINK, *Bell Telephone Laboratories* (introduced by Jacob F. Dewald).—A new effect can be observed when a biased square wave field is applied to a c domained crystal of $BaTiO_3$ containing a few a domains. When the field is applied and the sample is viewed with a polarizing microscope, there appear a large number of small c domains which move horizontally in well-defined paths. The motion only occurs above a domains and is in straight line paths perpendicular to the a domain edges. The sidewise velocity of the c domains above a given a domain varies directly as the field's frequency and exponentially as the reciprocal of the field-on-the-low-field-pulse. A model accounting for these observations invokes a novel displacement, which a spike-shaped c domain undergoes when it penetrates an a domain. The effect has been used to estimate the velocity of of propagation in the forward direction of nucleated steps on the sides of the c domains. This velocity was found to be of the order of 1 cm/sec at room temperature, and is believed to be independent of field.

WEDNESDAY AFTERNOON AT 2:15
WSU McGregor Memorial
Conference Center Room B
(E. BURSTEIN presiding)

Session XA. Post-Deadline Papers if Any

THURSDAY MORNING AT 9:30
WSU Community Arts Auditorium
(W. F. BUSSE presiding)

High-Polymer Physics V

Invited Papers

Y1. Effects of Molecular Weight Distribution on the Physical Properties of Polystyrene. H. W. MCCORMICK, *The Dow Chemical Company.* (40 min.)

Y2. Time and Temperature Dependence of the Ultimate Mechanical Properties of Amorphous Elastomers. T. L. SMITH, *Stanford Research Institute.* (40 min.)

Contributed Papers

Y3. Stress as a Reduced Variable: Stress Relaxation on SBR Rubber at Large Strains. PAUL J. STEDRY AND ROBERT F. LANDEL, *California Institute of Technology.*—In Ferry's formalized concept of time-temperature superposition in amorphous polymeric systems, the treatment is limited to strains sufficiently small that the (isochronal) stress-strain law is Hookean. This restriction is now examined and a method of circumventing it is proposed. Assuming that all time dependence is included in the modulus $E(t)$, any real stress-strain law can be written as $\sigma = E(t)\epsilon f(\epsilon)$, where $f(\epsilon)$ is some unspecified function of strain only. By defining $\sigma^* = \sigma/f(\epsilon)$ as a reduced stress results in a linearized law, which is then employed in place of Hook's law. This concept is tested on stress relaxation data of SBR at strains of 50 to 650%, over the temperature range of −15° to +80°C and a time scale of 1 to 10^4 min. The isochronal stress-strain curve can be described by the Martin, Roth, Stiehler equation, so that $f(\epsilon) = \alpha^{-2}\exp A(\alpha - \alpha^{-1})$, where $A = 0.40$. Use of the reduced stress concept collapses all data at a given temperature to a single curve within the rather large experimental error. These curves can then be superposed by the usual translation along the time scale to generate the final stress relaxation curve. The

stress relaxation modulus obtained from this superposed curve is compared with that calculated from a reduced stress-strain curve obtained in the manner of Smith.

Y4. The Mechanical and Optical Properties of Fluorocarbonamidene Elastomers.* H. KAWAI† AND R. S. STEIN, *University of Mass.*—Copolymers of completely fluorinated mono and diamidenes were obtained from H. Brown (University of Florida) and were converted to films by sintering under heat and pressure. The stress and birefringence of these were measured as a function of strain, time, and temperature. The films are relatively weak, breaking at elongations of 50–100% and at stresses of the order of 10–20 psi. The stress-strain and stress-temperature curves indicate that the elasticity is mostly of entropy origin. There is little observable stress relaxation up to the breaking point. Breaking probably occurs at imperfections which may be physical bonds between gel particles. The birefringence increases slightly during relaxation. It decreases upon heating at constant length but increases again upon cooling. $(\partial E/\partial l)_{VT}$ determined from the force-temperature behavior is negative. These facts indicate a tendency toward crystal-like order. However, no evidence of crystallinity is found by x-ray diffraction.

* Supported in part by a contract with the Office of Naval Research and in part by a grant from the National Science Foundation.
† On leave from Department of Textile Chemistry, Kyoto University, Japan.

Y5. Pressure Dependence of Viscosity and Relaxation Times and its Interpretation in Terms of Free Volume. JOHN D. FERRY AND ROBERT A. STRATTON, *University of Wisconsin.*—According to the simplified Doolittle free space equation, the ratio a_{AB} of relaxation times for a given shear relaxation process in states A and B is given by $\ln a_{AB} = 1/f_B - 1/f_A$, where f is the relative free volume. This relation has been successfully applied to the dependence of relaxation times on temperature (WLF equation), on side chain length in a homologous series of polymers, and on the proportion of added diluent, provided f does not exceed a maximum value (about 0.08) beyond which specific effects of molecular structure are considered to play a prominent role. When the pressure is varied, the relation takes the form $\log a_P = \beta_f(P_B - P_A)/2.303[f_A^2 - f_A\beta_f(P_B - P_A)]$, where f_A is the relative free volume at P_A and β_f is that portion of the macroscopic compressibility ascribable to collapse of free volume. By plotting $(P_B - P_A)/\log a_P$ against $P_B - P_A$, f_A and β_f are readily obtained from experimental data. Examples are shown in which these parameters are found to have the correct magnitude.

Y6. On Mechanical Breakdown of a Biaxially Oriented Model Linear High-Polymer Solid.* J. E. OSBORN AND C. C. HSIAO, *University of Minnesota.*—A mathematical analysis is given to describe the effect of biaxial orientation on the tensile strength of a model linear polymer solid consisting of a system of oriented spring elements. Referring to an orthogonal set of axes the stress tensor in the vicinity of a point is found to be

$$\sigma_{ij} = C \int \epsilon_{m,n} s_m^* s_n^* s_i^* s_j^* \rho^* d\omega^*,$$

where C is a constant, $\epsilon_{m,n} s_m^* s_n^*$ is the strain of the spring with its orientation given by the unit rector s_i^*, ρ^* is the density of the probability distribution function of the orientation of the springs, and $d\omega^*$ is the solid angle. The fracture stress for any degree of biaxial orientation is evaluated as a function of orientation strain and the unoriented strength. Some available experimental data are found to agree fairly well with the predicted fracture surface.

* Supported in part by the U. S. Atomic Energy Commission.

Y7. Wave Functions and Energy Eigenvalues for the Polytetrafluoroethylene Chain. YOH-HAN PAO AND R. F. BJORKLUND,* *Polychemicals Department, E. I. Du Pont de Nemours and Company.*—The paper reports on a quantum mechanical investigation of an isolated polytetrafluoroethylene molecule. The purpose of this investigation is twofold: to find the energy gap between filled and empty electronic bands, and to determine the energy required to change the conformation of the molecule. Molecular wave functions are constructed from Bloch sums taken along the four rows of fluorine atoms. The basis functions used are Gaussian approximations to $2p$ and $3s$ atomic orbitals. The suitability of this choice is tested in a preliminary calculation of the dissociation energy of the hydrogen fluoride molecule.

* Present Address: Western Regional Research Laboratory, Albany, California.

Y8. Protection against Radiation Damage in Polymethylmethacrylate Caused by High-Energy Electrons and by Ultraviolet Light. D. G. GARDNER* AND L. M. EPSTEIN, *Westinghouse Electric Corporation.*—Although while solid solutions of scintillators in plastics have been studied extensively as radiation detectors, relatively little work has been done on such systems from the point of view of protection of the bulk plastic from radiation-induced damage through the action of scintillators. In the present work polymethylmethacrylate (PMMA) was chosen as the plastic, and the primary scintillators were pyrene and *p*-terphenyl. These scintillators were compared with such other organic materials as benzene, xylene, ethyl benzene, and with such inorganic materials as manganese acetate and lead acetate. A comparison of the uv and the 2-Mev electron damage work clearly shows that the breakdown by fast electrons proceeds in part through different mechanisms than in the uv case. It appears that only a fixed fraction of the energy lost by the fast electrons in PMMA is susceptible to removal by the scintillators. A correlation of the uv and high energy protective effects has been proposed.

* Present address: Department of Chemistry, University of Arkansas, Fayetteville, Arkansas.

THURSDAY AFTERNOON AT 2:00

WSU Community Arts Auditorium

(S. KRIMM presiding)

High-Polymer Physics VI

Invited Papers

Z1. Application of Electron Paramagnetic Resonance Spectroscopy in Studying the Effects of Radiation on Polymers. R. S. POWELL, *General Electric Company.* (30 min.)

Z2. Internal Friction and Nuclear Magnetic Resonance in Polyoxynethylene. N. G. MCCRUM, *E. I. du Pont de Nemours & Company.* (30 min.)

Contributed Papers

Z3. NMR Absorption in Teflon Fibers. D. HYNDMAN AND G. F. ORIGLIO, *American Viscose Corporation.*—From the point of view of NMR spectra oriented fibers of polymers can be regarded as single crystals to a first approximation and can, therefore, yield more information than an unoriented specimen. Nuclear magnetic resonance absorption in oriented polytetrafluoroethylene fibers has been investigated in the temperature range 170°K–380°K. The sample, in the form of a parallel bundle of fibers, showed a marked dependence of line-shape on the direction of the applied magnetic field over the temperature range studied although the observed anisotropy was much greater above 285°K than below. Changes occurring in the line-width and second moment at around 285°K indicate a rotational disorder transition in the crystalline regions of the polymer, and serve to illustrate the advantages of using oriented fibers in the NMR investigation of semicrystalline polymers.

Z4. Effect of Reactor Irradiation on the Tensile Strength of Uniaxially Oriented Polyethylene Terephthalate.* C. C. HSIAO AND S. T. CHOW, *University of Minnesota.*—A series of uniaxially oriented polyethylene terephthalate fibers irradiated in a nuclear reactor have been investigated. On the basis of tensile studies, the ultimate tensile strength is found to decrease as the dose of reactor irradiation increases. However, the ultimate tensile strength is found to increase when the degree of molecular orientation increases. But after the samples have received a fairly high dose the tensile strength becomes practically nil. The x-ray diffraction scans of the non-irradiated samples with low degrees of orientation indicate very little crystallinity, whereas the very definite diffraction peaks associated with the irradiated and oriented samples indicate a definite trend toward crystallinity.

* Supported in part by the U. S. Atomic Energy Commission.

Z5. Effect of Temperature and Reactor Irradiation on Tensile Properties of Biaxially Oriented Polyethylene Terephthalate.* A. HAYNES AND C. C. HSIAO, *University of Minnesota.*—Samples of biaxially oriented polyethylene terephthalate irradiated in a nuclear reactor have been investigated at five temperature levels from −150° to 350°F. From tensile studies for all the temperature levels, the ultimate tensile strength decreases markedly to a minimum uniform value upon receiving a reactor irradiation dose having a thermal neutron bombardment component of 10^{18} nvt and over. The modulus of elasticity for the nonirradiated samples increases as the temperature decreases. However, for the irradiated samples the modulus of elasticity at room temperature is greater than that at either higher or lower temperatures.

* Supported in part by the U. S. Atomic Energy Commission.

Z6. Versatile Instrument for Measuring Processing Characteristics of Rubber Mixes: the Cepar Apparatus. F. S. CONANT AND W. E. CLAXTON, *The Firestone Tire and Rubber Company.*—An apparatus and method are described for evaluating an elastic stiffness factor, rate of extrusion, hot recovery, scorch, and length and diameter of extruded material for uncured rubberlike polymers and compounded stocks. Some of the above properties are also obtainable on vulcanizates at high temperatures, up to 600°F. With a simple chamber substitution the apparatus is also adaptable for cure evaluations of rubberlike compounds. The complete unit has been termed the CEPAR (cure, extrusion plasticity and recovery) apparatus. In essence, the method describes a means of forcing a rubberlike material through an orifice of chosen diameter and of observing the instantaneous deformation and subsequent extrusion rate that occurs under constant driving load. Results are given which show various applications of the apparatus. Demonstrated advantages of the method over conventional processability tests include time saving, stock saving, and applicability to stocks normally considered either too hard or too soft for satisfactory testing. In a laboratory where a large selection of test instruments is not feasible, the versatility of the apparatus described should prove very advantageous, especially when combined with the aforementioned cure phase of the apparatus.

Z7. Color Phenomena in Polymethyl Methacrylate Fractures. I. WOLOCK, *Naval Research Laboratory,* S. B. NEWMAN AND S. G. WEISSBERG, *National Bureau of Standards,* AND J. A. KIES, *Naval Research Laboratory.*—Individual geometric markings on the fracture surfaces of polymethyl methacrylate have been observed to be demarcated by color. The matching markings on both sides of the failure can be shown to bear complementary colors. By varying the velocity of fracture, however, it is possible to obtain color distributions with varying degrees of specificity for the surface markings. When examined immediately after failure, the colored fracture surfaces are found to be covered with an apparently discrete film. The film which is softer than the matrix may be removed either mechanically or by solvents, but the colors are not uniquely dependent on the presence of the film since other variables, such as heat, may remove the colors without removing the film. The geometric figures apparent as fracture markings maintain their physical identity despite the removal of film or color or both. A simple demonstration relating the phenomenon to first-order interference is possible by incorporating a metallized fracture surface into a thin-film interferometer of the type described by Tolansky.[1] Microspectroscopy reveals that the fracture colors are also first order. Properties of the film and surfaces revealed by optical and physical techniques will be described and illustrated.

[1] S. Tolansky, Nature **170**, 81 (1952).

SUPPLEMENTARY PROGRAMME

SP1. Calculation of Lattice Specific Heats in the Harmonic Approximation. A. F. STEVENSON, *Wayne State University.**—The usual method for calculating the lattice contribution to the thermodynamic properties of crystals makes use of the frequency distribution function. A method is given, which enables the lattice free energy, specific heat, etc., to be expressed explicitly in terms of the polynomial whose roots determine the natural frequencies when periodic boundary conditions are used. In this way, the explicit determination of the frequencies is avoided. For the numerical calculation of specific heats in terms of interaction constants this method should be less laborious than the usual one. A numerical example will be given.

* To be called for at the end of Session W if the Chairman rules that time permits.

Author Index to Papers Presented at the 1960 Detroit Meeting

Abrahams, E.—FA3
Adawi, I.—V1
Alers, G.—E4, JA3
Alger, R. S.—DA10
Allgaier, R. S.—CA10
Anderson, T. H.—DA10
Arndt, R.—B8
Arnold, G. W.—IA1
Artman, R. A.—IA4
Ascarelli, G.—V7, V8
Ascoli, A.—OA14
Aukerman, L. W.—IA3
Bachmann, L.—S11
Baker, J.—F1
Balluffi, R. W.—I1, OA5
Barredo, J. G.—KA6
Baruch, P.—VA1
Bate, R. T.—CA8
Batterman, B. W.—J5
Bauer, C. L.—QA10
Bauer, S. H.—DA11
Becker, J. H.—X11
Beckman, Olof—RA5
Bedo, D. E.—J3
Beer, A. C.—CA8
Beeler, J. R., Jr.—D6
Bennett, A. I.—H5, H6
Berger, M.—M5
Bergstrom, B. H.—S8
Berry, B. S.—D1
Bestul, A. B.—K4
Bjorklund, R. F.—Y7
Blair, J.—GA10
Blau, H. H.—K1
Blaugher, R. D.—GA5
Blewitt, T. H.—B5, B10
Blount, E. I.—G11
Blumberg, W. E.—QA1
Blume, R.—N3
Blunt, R. F.—X11
Bolef, D. I.—JA1
Boney, F. A.—M1
Bowers, R.—G9
Boyd, D. R.—R4
Braunstein, R.—W4
Bray, P. J.—A3
Bray, R.—V4, V5
Bredt, J. H.—OA3
Brockhouse, B. N.—W6
Bron, W. E.—QA12
Brophy, J. J.—R2
Brout, R.—BA3, BA4, O5
Brown, D. M.—V4, V5
Brown, E.—J4, OA2
Brown, S. C.—V7, V8
Buckley, D. J.—M5
Budnick, J. I.—GA7
Burke, J. R., Jr.—CA10
Burns, G.—F13
Burstein, E.—W2
Caglioti, G.—W6
Cahn, J. W.—Ba8
Callaway, J.—G7
Caswell, H. L.—GA8
Catalano, S. B.—H8
Chambers, R. H.—D5
Chipman, D. R.—J5
Chow, S. T.—Z4
Choyke, W. J.—CA5
Chynoweth, A. G.—FA6
Claxton, W. E.—Z6
Cleland, J. W.—VA3
Cloud, W. H.—RA3
Cohen, D. A.—G8
Cohen, M. H.—G10, O1, O2, Q1
Coleburn, N. L.—D7, X12
Coleman, R. V.—D10, S9
Coltman, R. R.—B5, B10
Conant, F. S.—Z6
Conwell, E. M.—V9
Coopersmith, M.—BA4
Corbett, J. W.—B3, VA8, VA9
Corelli, J. C.—IA6
Cowperthwaite, M.—DA11
Crawford, J. H., Jr.—VA3, VA4
Cunningham, R. W.—R5
Curtis, O. L., Jr.—VA4
Czyzak, S. J.—S2
Damask, A. C.—OA13, OA14
Danielson, G. C.—R7
Darnell, F. J.—RA4, RA8
Dash, W. C.—S1
Decius, J. C.—KA3
Demars, G. A.—F2, F3
Devlin, Shaun—CA4
Dexter, R. N.—NA3
Dienes, G. J.—IA2, OA13
Dimmock, J. O.—NA6
Ditzenberger, J. A.—CA6
Donn, B.—KA5
Dresselhaus, G.—GA1, GA2
Dresselhaus, M. S.—GA1, GA2
Dreyfus, R. W.—X3, X4
Duncan, R. C., Jr.—NA2
Dyer, L. D.—S6
Eberhardt, H. E.—P1
Eck, T. G.—C3
Eckstein, Y.—JA4
Edwards, D. F.—NA5
Edwards, D. M.—G7
Efremov, N.—CA11
Ehrenreich, H.—O2, CA2
Ehrenson, S.—DA6
Ekstein, H.—J2
Ellerbeck, L. D.—R7
Elmgren, J. A.—R8
Emrick, R. M.—OA6
Englert, F.—O4, O5
Epstein, L. M.—Y8
Etzel, H. W.—QA13
Everett, G. E.—X5
Fan, H. Y.—CA7, VA6, VA7
Faust, J. W., Jr.—H1, H2, H3, H4
Feher, G.—QA1
Ferry, J. D.—Y5
Feuersanger, A.—V14
Fiegel, L. J.—D9
Filler, A. S.—W2
Finnemore, D. K.—GA4
Flippen, R. B.—RA7
Fontanella, E. L.—B3
Fowler, V. J.—V10
Fraga, S.—DA8
Frank, R. C.—K5
Frank, Wm.—NA7
Frankl, D. R.—V14
Fredericks, W. J.—R6
Frederikse, H. P. R.—X11
Freitas, L. G.—H12
Friedberg, S. A.—RA7
Friedman, A. N.—C5
Fritz, J. N.—O9
Fritzsche, H.—FA1
Frost, R. T.—IA6
Gager, W. B.—N4
Galt, J. K.—Q2
Gardner, D. G.—Y8
Geballe, T. H.—FA2
Geil, P. H.—U9, U10
Gilman, J. J.—E1
Gilvarry, J. J.—S8
Ginsberg, I. W.—DA14
Glarum, S. H.—KA2
Goedecke, G. H.—J4, OA2
Goetzberger, A.—FA9
Goland, A. N.—IA4
Goldburg, W. I.—N9
Gordon, R. B.—QA10
Gordon, W. L.—C3
Graft, R.—IA3
Guentert, O. J.—R10
Hacskaylo, M.—QA4
Haken, H.—O4, BA3
Hall, J. J.—V6
Halloran, M.—NA3
Ham, F.—G1
Ham, J. S.—M2
Hamilton, D. R.—H1, H2, CA5
Handler, P.—V13
Harman, T. C.—CA9
Harrison, W. A.—G5
Harrity, J. W.—VA2
Hasegawa, H.—F12, NA8
Hass, Marvin—W1
Haszko, S. E.—R1
Haynes, A.—Z5
Hebel, L. C.—N8
Heeger, A. J.—RA5
Heller, W. R.—B2, L4, QA12
Heller, W. R.—QA12
Hensler, D.—NA3
Hillig, W. B.—K2
Hines, R. L.—B8
Hoffman, J. D.—T2
Hollar, E.—NA3
Hopfield, J. J.—CA3
Hopkins, D. C.—GA6
Howard, R. E.—NA8
Horiye, H.—VA2
Horsfall, R. C.—O11
Houston, B. B.—H9
Hsiao, C. C.—Y6, Z4, Z5
Hudson, D. E.—R8
Huggins, M. L.—U1
Hulm, J. K.—GA5
Huntington, H. B.—OA2, OA12
Huyett, M. J.—M4
Huzinaga, S.—DA7, DA9
Hyndman, D.—Z3
Jackson, J. J.—D8
Jaffe, L. D.—S10
Jarrett, H. S.—RA3, RA8
Jastram, P. S.—KA1
John, H. F.—H1, H2, H3, H4

Johnson, R. A.—OA2
Jones, M. D.—X7
Jones, R. V.—N1
Joseph, A. S.—C3
Joseph, R. I.—BA7
Kaminow, I. P.—N1
Kammer, E. W.—C10, C11
Kane, E. O.—FA4
Kauffman, J. W.—OA10, OA11
Kaus, P. E.—G2
Kawai, H.—Y4
Keating, D. T.—A2
Keedy, D. A.—M7
Keith, H. D.—T1
Kernohan, R. H.—B7
Keyes, R. W.—C6
Khoury, F.—U3
Kies, J. A.—Z7
Kikuchi, C.—F1, F8
Kikuchi, R.—O8, BA8
Kikuchi, T. T.—J2
King, J. C.—A4
Klabunde, C. E.—B5, B10
Klauder, J. R.—C7
Klein, C. A.—R11
Klemens, P. G.—GA11
Klick, C. C.—QA11
Koehler, J. S.—D8, MA1, OA3
Koenig, S. H.—C5, V6, W5
Kohn, W.—N7
Koster, G. F.—F2, F3
Kranendonk, V.—W10, W11
Krumme, J. B.—R9
Krimm, S.—L6
Kunzler, J. E.—C7
Laff, R. A.—CA7
Lambe, J.—B11, F1, F8
Landel, R. F.—Y3
Landwehr, G.—V13
Larsen, R. E.—OA13
Lassettre, A. N.—P3
Laukonis, J. V.—S9
Laurance, N.—X1
Lawson, A. W.—JA4, OA7, X5
Lax, Benjamin—I3, NA4
Lax, M.—O7
Lazarus, D.—D10, OA4, OA6, X2
Lazazzera, V. J.—NA5
Lee, C. A.—FA5
Lee, R. W.—K5
Leivo, W. J.—R9
Levy, P. W.—QA2, QA3
Levy, R. A.—IA5
Li, James C. M.—S7
Ligenza, J. R.—H10, H11
Lindsay, L. P.—DA12
Link, G. L.—X14
Liu, L.—G10
Logan, R. A.—FA6
Long, D.—V12
Longini, R. L.—H5
Longo, T. A.—FA7
Lowell, R. C.—OA8
Ludwig, G. W.—F10, F11
Lundberg, J. L.—M4
Luttinger, J. M.—Q3
Machlup, S.—O13
Maeda, S.—DA12
Manning, J. R.—OA1
Mapother, D. E.—GA4, GA6
Maradudin, A. A.—O11, W3, W8
Marcus, P. M.—G6, K6
Marshall, S. A.—F6
Martens, H. E.—S10
Mascarenhas, S.—H12
Masuda, Y.—N5
Matsuoka, S.—U5
McAfee, K. B., Jr.—K3
McCormick, H. W.—Y1
McCrum, N. G.—Z2
McDonald, R. S.—VA9
McFee, J. H.—K6
McIntyre, D.—L1
McIrvine, E. C.—O10
McKelvey, J. P.—H7
McLean, A. D.—DA5
Meiboom, S.—N10
Melamed, N. T.—JA1
Menes, M.—JA1
Merriam, M. F.—QA9
Meshii, M.—OA10, OA11
Meyers, N. H.—GA3
Milford, F. J.—N4
Miller, A.—FA3
Miller, N. C.—OA12
Mitchell, P. V.—QA5, QA6
Montgomery, H. C.—FA5
Moore, A. R.—I2
Morgan, T. N.—V2
Mori, T.—OA10, OA11
Moriya, T.—BA1
Mozer, B.—QA3
Muldawer, L.—C12
Mullen, J. G.—OA4
Mulliken, R. S.—DA1, DA5
Myers, J.—V12
Nakagaki, M.—L4
Nathan, M. I.—V3
Nelson, C. M.—X10
Nerses, V.—OA12
Newman, R.—RA1
Newman, S. B.—Z7
Niegisch, W. D.—U2
Nilan, T. G.—MA2
Nixon, J. D.—O13
Norton, R. E.—G2
Norton, R. M.—X9
Nowick, A. S.—D1, X3
O'Hara, S.—H6
Okano, K.—L5
Olechna, D. J.—CA2
Origlio, G. F.—Z3
Orr, W.—S11
Osborn, J. E.—Y6
Overton, W. C., Jr.—W7
Padden, F. J., Jr.—U3
Pagel, B. R.—R3
Pao, Yoh-Han—Y7
Papazian, L.—L4
Paré, V. K.—B4, D2
Parker, R. A.—X13
Patel, J. R.—E3
Patrick, Lyle—CA5
Patterson, D. A.—X8
Pearlstein, E. A.—QA8
Pesch, J. A.—D9
Peter, M.—F5
Peterlin, A.—T3
Peters, C. W.—P2
Peters, P. C.—IA3
Peterson, G. A.—G3
Phelps, F. T.—QA8
Philipp, H. R.—X6
Philippoff, W.—M6
Phillipson, P. E.—DA4, DA6
Pierce, C. B.—X2
Plaza, A.—U7
Poll, J. D.—W10
Pollak, M.—FA2
Portis, A. M.—Q4, RA5
Powell, R. S.—Z1
Power, M.—CA3
Powers, J.—M7
Pratt, G. W., Jr.—O3
Prewitt, C. T.—R10
Price, P. J.—C4
Puff, R. D.—O3
Pugh, T. L.—L4
Queisser, H. J.—FA8
Quinn, D. J.—GA7
Quinn, J. J.—W9
Ramaswamy, M. K.—KA1
Ramdas, A. K.—VA6, VA7
Ransil, B. J.—DA3, DA5, DA8
Rayne, J. A.—JA2
Redfield, A.—N3, N5
Reiffel, L.—KA4, X7, X9
Reitz, J. R.—G8
Reneker, D. H.—JA4, U10
Reynolds, D. C.—S2
Rhodes, M. B.—U6
Rhodin, T.—S11
Rimai, L.—F2, F3
Roberts, S.—C8
Roothaan, C. C. J.—DA9
Rosenblatt, D. B.—IA2
Rosenblum, B.—NA2
Roth, W. L.—RA2
Rothmann, J. C.—IA2
Rothstein, J.—VA11
Rothwarf, F.—C12
Rowland, T. J.—N6
Rupprecht, G.—R12
Ruth, Ralph P.—H8
Sack, R.—W8
Sadler, M. S.—RA3, RA4
Sakamoto, M.—W6
Salkovitz, E. I.—C10, C11, RA9
Sato, H.—BA6
Schalow, A. L.—F5
Schatz, P. N.—DA12
Schindler, A. I.—RA9
Schlömann, E.—BA9
Schlosser, H.—G6
Schrieffer, J. R.—O1
Schultz, J.—D5
Scott, G. C.—NA9
Scouler, W. J.—QA14
Segall, B.—G4
Seidensticker, R. G.—H1, H2
Shaw, R. W.—GA4, GA6
Shenker, H.—V11
Shiozawa, L. R.—CA4
Shockley, William—FA8, FA10
Sidles, P. H.—R7
Siegel, B.—S11
Sihvonen, Y. T.—R4
Simmons, R. O.—OA5
Sinclair, R. N.—W6
Singwi, K. S.—J1

Sjölander, Alf—J1
Slack, G. A.—GA9, RA2
Sladek, R. J.—C1
Slichter, W. P.—U4
Smakula, A.—QA14
Smith, G. E.—X5
Smith, T. L.—Y2
Smith, W. J.—H5
Smoluchowski, R.—B6, B9, QA5, QA6, QA7, QA9
Solow, M.—D7, X12
Sonder, E.—VA5
Spector, H. N.—O6
Spilners, Aija—B6
Spitzer, W. G.—H10, H11
Sproull, R. L.—S3
Statz, H.—F2, F3
Stedry, P. J.—Y3
Stein, R. S.—M7, U6, U7, Y4
Stern, Edward A.—C9
Stern, F.—J6
Stevenson, A. F.—DA14, L3, SP1
Stevenson, M. J.—NA1
Stratton, R. A.—Y5
Struthers, J. D.—CA6
Suhl, H.—BA2, N2
Swan, P. R.—U2
Swets, D. E.—K5
Swihart, J. C.—GA3
Tabibian, R. M.—L4
Taft, E. A.—X6
Takamura, Jin-Ichi—OA9
Tansal, S.—GA3
Teaney, D. T.—RA5
Templeton, L. C.—VA5
Terhune, R. W.—F1
Thomas, D. G.—CA3
Thompson, D. O.—B4, D2
Thomson, Robb,—S5
Tichelaar, G. W.—D10
Title, R. S.—F14
Tomboulian, D. H.—J3
Tomizuka, C. T.—OA7, OA8
Townsend, J. R.—B1
Tucker, E. B.—F4
Turnbull, D.—A1
Turner, T. J.—D3, D4
Vander Velde, J. C.—VA10
van Lint, V. A. J.—VA2
Van Putten, J. D., Jr.—VA10
van Roosbroeck, W.—O12
Vidale, G. L.—DA13
Vineyard, G. H.—MA3
Von Gottfried, L.—D6
Vosko, S. H.—N7
Wada, Eiichi—L4, L5
Waldorf, D. L.—JA5
Walker, R. M.—B3
Wall, F. T.—L2
Wallace, D. C.—GA12
Wallis, R. F.—W3
Wasilik, J. H.—X13
Watkins, G. D.—MA4, VA8, VA9
Watson, W. K. R.—G2
Watts, H. V.—X7
Webb, L. A.—DA10
Weber, M. J.—F2, F3
Wechsler, M. S.—B7
Weeks, R. A.—X10
Weiss, A. W.—DA2
Weiss, G. H.—W8
Weissberg, S. G.—Z7
Wernick, J. H.—R1
West, F.—BA5
Wheeler, R. G.—NA6
Whelan, J. M.—CA6
White, D. L.—RA6
White, F. A.—IA6
Whitmore, F. C.—M3
Wiegand, D. A.—QA5, QA6, QA7, QA9
Wikner, E. G.—VA2
Wilchinsky, Z. W.—U8
Wiley, R. C.—D7, X12
Wilk, M. B.—M4
Willardson, R. K.—CA8
Williams, G. P., Jr.—D3, D4
Williams, R.—CA1
Wilsdorf, H. G. F.—E2
Wilson, P. R.—U7
Wojtowicz, P. J.—BA7
Wolfe, R.—R1
Wolock, I.—Z7
Woodbury, H. H.—F10, F11
Woods, A. D. B.—W6
Wortman, R. M.—B9
Wright, G. B.—NA4
Yarnell, J.—W5
Yoshimine, M.—DA9
Young, D. R.—GA3
Young, F. W., Jr.—S4

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Park Shelton Hotel—Woodward at Kirby, C. B. Loftis, General Manager
Sheraton-Cadillac Hotel—Washington Boulevard and Michigan, Martin Stoskopf, Front Office Manager
Statler Hilton Hotel—Washington Boulevard and Grand Circus Park, Lloyd Stalcup, Sales Manager

Rates for Rooms with Private Bath

	Singles	*Doubles or Twins for Two*
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AMERICAN PHYSICAL SOCIETY

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For Arrival March ..... at ..... a.m. ..... p.m., Departure, March ..... at ..... a.m. ..... p.m.

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Proceedings of the American Physical Society

Minutes of the 1959 Summer Meeting in the West at the University of Hawaii, Honolulu, August 27–29, 1959

THE 1959 Summer Meeting on the West Coast of The American Physical Society was held at Honolulu, Hawaii, on Thursday, Friday, and Saturday, August 27, 28, and 29, 1959. The area for the Pacific Coast meetings has been defined as lying west of the Continental Divide. The trouble with this agreement is that it does not specify which continent. This is the largest single jump in distance ever taken by the Society for one of its meetings, and yet it was still within the United States, the meeting having taken place within a week of the accession of Hawaii as the fiftieth state in the Union. The meeting was very successful, and it was a wonderful opportunity for tired physicists to recoup a little before starting their fall schedules. It is unfortunate that the earliest anticipated return to Hawaii for a meeting is as far away as 1965.

There were 54 invited papers and 131 contributed papers and only one contributed paper was read by title. The total paid registration was 202, and the attendance at the banquet was approximately 190. Cocktails before the banquet were contributed by the Hawaiian Electric Company. The presiding officer was the President of the Society, Professor G. E. Uhlenbeck. The after-dinner speaker was Chancellor G. T. Seaborg who spoke on "The Scientist as Administrator." The Society was welcomed to the campus of the University of Hawaii by President L. H. Snyder. The Local Chairman for this meeting was Professor K. Watanabe to whom we owe a good deal of thanks and who supplied the traditional leis for many of the occasions.

William A. Nierenberg,
Local Secretary for the Pacific Coast
Department of Physics
University of California
Berkeley 4, Calif.

Errata Pertaining to Abstracts Q8 and R12 of the 1959 Honolulu Meeting

(Series II, Vol. 4, No. 6)

Q8, by Arthur H. Muir and Felix H. Boehm. In the title line, instead of "Ta^{191}" read "Ta^{181}."
R12, by Sherwood Parker, Burton J. Moyer, and John Mosher. The last author's name should read "Osher" not "Mosher."

Minutes of the 1959 Thanksgiving Meeting

IN 1959 the Thanksgiving Meeting of The American Physical Society was transposed from Chicago to Cleveland, and specifically to the campus of the Case Institute of Technology, our host. This was our first visit to Cleveland since 1949. Snow lay on the ground as it then did, and was replenished from time to time as it was then, but never strongly enough to hinder coming or going. In 1949 we had to distribute our sessions among three institutions, but in the meanwhile Case has expanded its facilities so much than in 1959 it could receive them all.

We usually have a sharp drop in attendance when the Thanksgiving meeting is moved away from Chicago, and consider this not too great a price to pay, once each several years, for the privilege of convening in a different neighborhood. On this occasion the price was unusually low. The registration of 472 compared very favorably with last year's Chicago figure of 563, and the number of contributed papers, 151 vs 160, was changed by only a little. The distribution of these among subjects was fairly conventional, semiconductors and reactions of transmutation taking the lead; a singularity was the almost total absence of papers on apparatus of nuclear physics. Of invited papers the largest coherent groups were formed by those on the first fruits of the satellite Explorer VI, and those on strange particles. The programme of invited papers we owe largely to the recommendations of a Committee appointed for the purpose, partly to the Cleveland Physics Society, and partly to the Ohio State University.

The banquet of the Society was held on Friday evening in the Wade Park Manor Hotel. The attendance (215) was a much larger fraction of the total registration than is customary, and the dinner was exceptionally good. The Acting President of Case Institute of Technology welcomed us with cordial words. The after-dinner speaker having been prevented from coming by sudden illness, our Vice-

President V. F. Weisskopf served in his place and spoke almost incredibly well on ten hours' warning.

The banquet was framed in by events for which we are beholden to hospitable hosts: a cocktail party preceding, which we owe to Clevite Corporation (Electronics Research Division), General Electric Company (Lamp Division), and National Carbon Research Laboratories; and a beer party following, which we owe to Carling Brewing Company and the Cleveland Physics Society.

Great is our debt to the Chairman of the Local Committee, Leonard O. Olsen, and to his Committee members, who were J. C. Bowman, T. G. Eck, William Gordon, James Hooper, Carl Kenty, J. K. Major, and Frederick Reines.

The Council met on Saturday afternoon. Frederick Seitz, incoming Vice-President of the Society, was named to the Governing Board of the American Institute of Physics for a three-year term. A supernumerary Dannie Heineman prize for outstanding work in mathematics was offered and accepted; it will be awarded during 1960.

Elected to Fellowship on November 28, 1959: Kenneth R. Atkins, Robert Demo Bent, David F. Bleil, Esther M. Conwell, Richard B. Curtis, Richard L. Doan, Rex G. Fluharty, Georg Hass, Abraham Klein, J. A. Krumhansl, H. Pierre Noyes.

Elected to Membership November 28, 1959: Ryuzo Abe, *Carlos R. Abeledo, Edward Adelson, *David C. Ailion, *John E. Alberghini, Carl A. Alexander, Warren R. Alexander, Carl W. Allen, Rolf M. Ammann, *Hugh R. Anderson, Bernell E. Argyle, *L. Scott Arighi, *Wallace Arthur, *Raymond F. Askew, Inger M. Asplund, Heinz H. Averdung, Stanley E. Babb, Jr., *Stephen D. Baker, Philip K. Baltzer, Bani R. Banerjee, *Angelo Bardasis, Luther C. Barcus, Albert H. Barlich, Zoilo M. Bartolome, James Bates, Michael H. Bauer, Jr., Rene Baus, *James W. Beatty, Jr., George Bekefi, Myron H. Bengson, Frank K. Bennett, Mark J. Beran, Robert W. Berkstresser, Don A. Berlincourt, Richard L. Bersin, *Malcolm Bersohn, Bruno Bertotti, *Enid Bierman, David E. Bilhorn, Charles K. Birdsall, Albert A. Blank, Henry H. Blau, Jr., Richard D. Blaugher, Mitchel F. Bloom, Lewellyn T. Boatwright, Jr., *Frank L. Bordell, Richard H. Boyd, Charles A. Boye, Jr., Robert T. Bradbury, Jr., *Joseph A. Brandt, Joseph Branigan, Jr., *John J. Brehm, Jr., Donald B. Brick, *Kenneth L. Brinkman, Martin G. Broadhurst, *Carl N. Brooks, Ross M. Brown, *Ronald A. Bryan, *J. M. Buon, *J. Anthony Burke, *David C. Burnham, James W. Butler, *Amado Cabezas, *Andrew G. Cade, Paul J. Cahill, *Wynne Calvert, *William B. Campbell, *Bruce Cantrell, *Richard L. Carlin, *Philip J. Carroll, Jr., John Carstoui, *Elmer B. Carter, Everett H. Cathey, Jr., Avery Catlin, *Charles Chackerian, Jr., *John L. Challifour, Fang-Cher Chang, Yuan-Feng Chang, Francis M. Charbonnier, P. Chavasant, *C. T. Chen, *Boong Youn Cho, *Sang-Jean Cho, *Ronald A. Christensen, Eugene R. Christie, *Donald O. Christy, *John Phillips Church, J. Winston Churchill, Lewis C. Clapp, Joseph H. Clarke, Mary Margaret Clark, *Allan R. Clyde, Edward L. Cochran, Donald A. Cohen, *Martin G. Cohen, *Richard L. Cohen, *Gerald S. Cole, *Terrell A. Cole, Sam O. Colgate, *F. A. Collins, *Gerald G. Comisar, Richard L. Conklin, *Andrew P. Contogouris, D. C. Conway, *Glenn M. Cook, Melvin A. Cook, A. Lucile Cox, J. Conrad Crown, *Gary Culp, Donald E. Cunningham, Robert W. Cunningham, Paul E. Dalbec, John G. Dardis, *Edward J. Davies, *Lawrence W. Davis, *Yasuo Deguchi, Joseph L. Delaware, Fekete Denes, *Guillaume P. DeVault, John W. Dewdney, Irnee J. D'Haenens, *Isabelle B. Didier, *John Dockery, *J. Robert Dorfman, McLane Downing, Margaret V. Doyle, Richard Matthews Drake, Jr., Gerard J. Dreiss, Jean Dubois, Jean M. Dubois, Julain L. Dunlap, Donald A. Dunn, *Frank E. Durham, William H. Eberhardt, Peter J. Eccles, *W. Farrell Edwards, *Joseph A. Efird, *John F. Endicott, Arnold Engler, Henri Epstein, Brother Vitus Eric, Terry E. Ewart, *Bruce N. Fabian, Thomas A. Farley, Brian W. Faughnan, Lester Feinstein, *Ronald H. Felton, Lester M. Field, Adolph J. Flach, Jr., Gerard Flamand, Lyman J. Floyd, *John D. Fox, Mark P. Freeman, *David L. Fried, Henry Friedman, *Lionel R. Friedman, Albert N. Gabro, *Hugh L. 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Errata Pertaining to Paper W1 of the Cleveland Meeting
(Series II, Vol. 4, No. 7)

W1, by Carl Kenty. Instead of "Nitrogen Atom" read "Nitrogen Molecule."

Minutes of the 1959 Winter Meeting in the West at the California Institute of Technology, Pasadena, December 28–30, 1959

THE 1959 Winter Meeting of the West Coast of The American Physical Society was held at the California Institute of Technology in Pasadena on Monday, Tuesday, and Wednesday, December 28, 29, and 30, 1959. As usual, the weather was beautiful and a good deal of physics was discussed in the open patio around the coffee urns. The West Coast Winter Meetings have grown so considerably that there was great trepidation as to the capacity of the lecture halls. However, because of the excellent planning of the Local Committee, the meeting went very smoothly in this respect. The American Physical Society has been meeting in Pasadena on and off for about 45 years. Unfortunately, other people, such as the management of the Santa Anita Race Track, have discovered the desirability of meeting there at about the same time of year, and the hotel situation in Pasadena has become impossible. Nevertheless, we hope that the Institute will continue to invite us because of the great desire of most of our members to visit the Institute with some regularity.

There were 44 invited papers and 113 contributed papers. There was a special session on the detection of nuclear explosions which took place in the auditorium of the local high school. The total paid registration was 835 and the banquet attendance was 410.

This meeting set a very pleasant precedent, we hope, in that the first American Physical Society prize, sponsored by the Hughes Aircraft Company, was awarded. The recipient was Professor D. A.

Glaser, and the presentation was made at the banquet by Professor G. E. Uhlenbeck, President of the Society. The principal speaker was Professor R. P. Feynman and the subject of his talk was: "There's Plenty of Room at the Bottom." There was a cocktail party before the banquet supported by a number of the major research companies in the Southern California area. The Local Chairman for this meeting was Professor Ward Whaling who did a magnificent job in view of the logistic difficulties.

WILLIAM A. NIERENBERG,
Local Secretary for the Pacific Coast
Department of Physics
University of California
Berkeley 4, Calif.

Errata Pertaining to Abstracts I5 and P2 of the 1959 Pasadena Bulletin
(Series II, Vol. 4, No. 8)

I5, by V. J. Ehlers and W. A. Nierenberg. Instead of

$$^{67}\delta^{69} = {}^{67}\Delta_{\frac{1}{2}}{}^{69} - {}^{67}\Delta_{\frac{1}{2}}{}^{69} = (\Delta\nu/a)^{67}(\Delta\epsilon/a)^{69} - 1$$

read

$$^{67}\delta^{69} = {}^{67}\Delta_{\frac{1}{2}}{}^{69} - {}^{67}\Delta_{\frac{1}{2}}{}^{69} = (\Delta\nu/a)^{67}/(\Delta\nu/a)^{69} - 1.$$

P2, by Felix Schweizer and J. Reginald Richardson. In the last two lines, instead of "0.24±0.11 Mev," read "9.24±0.11 Mev."

Second Announcement of the 1960 Washington Meeting

The 1960 Washington meeting will be held from Monday through Thursday, April 25–28; the headquarters hotel is the Sheraton-Park; deadline will be past when this Bulletin appears. For additional details see the previous (Houston) issue of this Bulletin.

Preliminary Announcement of the 1960 June Meeting in Montreal

The **1960 June meeting will be held in Montreal,** on the campus of McGill University, on Wednesday, Thursday, and Friday, **June 15–17, 1960.** Of equal importance with the meeting dates is **June fourth, which is the latest date at which reservations will be accepted by our official hotel,** the Sheraton-Mt. Royal, Montreal, Canada. Montreal is a great and congested tourist center in the summer months, and its hotels feel themselves obliged to fix deadline dates of this character in order to do justice to their other clients. After this hotel is booked full, later applicants will be housed at the Laurentien: but write in any case to the Sheraton-Mt. Royal. Those who are willing to share twin-bed rooms will get accommodations more easily. Therefore be on the safe side and write as soon as possible to this hotel, not forgetting to say that you are a member of The American Physical Society coming for its meeting. At this convention we expect the participation of our Divisions of Electron Physics, Fluid Dynamics, and Plasma Physics. Deadline-day for abstracts is **Friday, April 8:** not later than that day the abstracts must be received at the office of the Society (American Physical Society, Pupin Physics Laboratories, Columbia University, New York 27, New York).

1960 Topical Conference on Neutron Diffraction in Relation to Magnetism and Chemical Bonding

A Conference on Neutron Diffraction in relation to Magnetism and Chemical Bonding, sponsored by Oak Ridge National Laboratory, the Office of Naval Research, and The American Physical Society, will be held in Gatlinburg, Tennessee, April 20–22, 1960. Members desiring more detailed information should write to E. O. Wollan, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Abstracts of contributed papers may be sent to E. O. Wollan (*not to the Secretary of the Society!*) and must reach him not later than March 1, 1960. *Abstracts must conform to the same regulations as are imposed on those submitted for general meetings of the Society; otherwise they will not be printed.* Take note that it is the prerogative of the management of the Conference to accept or decline contributed papers that are offered.

Second Topical Conference on Reactions between Complex Nuclei

A second conference on Reactions between Complex Nuclei will be held on May 2 and 3, 1960, at Gatlinburg, Tennessee. Any member of the Society who desires more detailed information should write to Dr. R. S. Livingston, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Abstracts of contributed papers may be sent to Dr. Livingston (*not to the Secretary of the Society!*) and must reach him not later than April 2, 1960. *Abstracts must conform to the rules and instructions imposed on abstracts for the general meetings, else they will not be published in the Bulletin.* Take note that the management of the Conference has plenary authority to accept or decline contributed papers that are offered.

1960 Gaseous Electronics Conference

The Thirteenth Annual Gaseous Electronics Conference will be held at Monterey, California, on October 12–14, 1960, under the sponsorship of the U. S. Naval Postgraduate School and that of the Division of Electron Physics of the American Physical Society. The scope of this conference embraces fundamental knowledge in the whole field of ionization and discharge in gases, not excluding plasma dynamics; but papers on specific devices will not be admitted.

Abstracts of contributed papers may be sent to N. L. Oleson, Conference Secretary, U. S. Naval Postgraduate School, Monterey, California, and must reach him not later than August 24, 1960. *Abstracts must conform to the same regulations as are imposed on those that are submitted for general meetings of the Society; otherwise they will not subsequently appear in this Bulletin.* As always, it is the prerogative of the management of the Conference to accept or decline contributed papers as it chooses. The Conference Committee will not accept a greater number of contributed papers than is compatible with its intent to keep the meeting within three days, to avoid simultaneous sessions, and to provide adequate time for presentation and discussion of the papers that are accepted.

MEETINGS AND DEADLINES THROUGH SUMMER 1960

Place	*Meeting dates*	*Deadline date*
Houston	March 4–5, 1960	Past
Detroit	March 21–24, 1960	Past
Washington	April 25–28, 1960	Past
Montreal	June 15–17, 1960	April 8

Abstracts for the meetings listed above are to be sent to KARL K. DARROW, American Physical Society, Columbia University, New York 27, New York, and must reach his office not later than the corresponding deadline date. Take note that abstracts mailed the day before deadline day often fail to arrive in time: the last postal delivery of the day usually comes to our office before 2 P.M. *Allow at least two days for abstracts sent by airmail from points east of the Mississippi, and longer for those sent from farther west.* Abstracts postmarked (at the point of dispatch) on deadline day are instantly rejected, and telegrams heralding their arrival are fruitless except in revenue to the telegraph company. *The privilege of contributing papers to meetings of the American Physical Society is restricted to the members of the Society and to nonmembers whose papers are sponsored by members.*

TOPICAL CONFERENCES (see above)

Gatlinburg	Neutron diffraction	April 20–22	March 1
Gatlinburg	Reactions between Complex Nuclei	May 2–3	April 2
Monterey	Gaseous Electronics	October 12–14	August 24

RULES AND INSTRUCTIONS FOR THE PREPARATION OF ABSTRACTS

The Council has ordered that abstracts shall be not longer than two hundred (200) words or the equivalent thereof. In reckoning equivalence, a footnote is equated to ten words (*but see new instruction below!*); each line in a table to ten words; a "display" formula—one that requires a line to itself—is an expensive luxury equated to forty words.

Two copies of each abstract must be sent to the appropriate office. They must be typewritten; *one must be an original*, the other may be an original or a carbon copy. *Carbon copies will not be accepted in lieu of originals:* they smear. *Abstracts must be double-spaced:* single-spaced manuscripts are too crowded to permit the editorial markings to be made with ease and clearness. *Each abstract must be confined to a single page:* if it is too long for a single page it is too long to be printed. If we receive an abstract typed on two pages, we print only its first page. *Write each abstract as a single paragraph:* the suppression of paragraphs costs time and labor to the editors. *Do not use very thin paper:* a sheet of very thin paper may cause extraordinary trouble when mixed with sheets of reasonable thickness. The American Institute of Physics will bless you if you type first the title of your abstract in lower-case with capitalized initials, then your name in capitals, then the name of your institution in lower-case underlined with capitalized initials. It is a pleasure to report that those who qualify for this blessing are increasing in number but are still quite a bit short of 100% of the total. Issues of the *Bulletin* are always appreciably delayed because the editors have to do what the authors should have done.

Remember the rule of the Council that, if an author submits more than one abstract, all but one must go onto the Supplementary Programme. In enforcing this rule, an abstract is credited to the author whose name appears first in the by-line.

It has now become an expensive business to make any change in an abstract, even the smallest, after the abstract has gone to press. By order of our Council "A change in an abstract will be permitted only at the discretion of the Secretary or his deputy, and only if TEN DOLLARS is enclosed with the letter in which the change is requested." As heretofore, an abstract will not be withdrawn from proof unless the asker sends ten dollars with his request.

New Instructions

(*a*) *If it is wished that two abstracts be scheduled consecutively, write on the first "To be scheduled before abstract ..... by ....." and on the second "To be scheduled after abstract ..... by ....."*

(*b*) *If a member insists that his paper be scheduled for a particular day or not on a particular day, he will get his wish, but usually at the price of having his contribution included in a session to which it is irrelevant.*

(*c*) *The Secretary and his deputies have been empowered by the Council to count a footnote either as ten words or as its actual length in words, whichever is the greater length.*

(*d*) *In general, all instructions about an abstract should be typed at the bottom of the page that has the abstract on it,* never *in a covering letter. Covering letters get separated from abstracts*!

The American Physical Society

OFFICERS OF THE SOCIETY FOR 1960

President	V. F. WEISSKOPF	Massachusetts Institute of Technology
Vice-President	FREDERICK SEITZ	University of Illinois
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Past Presidents now on Council: W. F. G. Swann, H. D. Smyth, J. W. Beams, and G. E. Uhlenbeck

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